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Calderon et al.

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(54) **STORAGE APPARATUSES AND RELATED METHODS FOR STORING TEMPERATURE-SENSITIVE ITEMS**

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F25D 11/00 (2006.01)

(52) **U.S. Cl.**
CPC ***F25D 11/006*** (2013.01); *F25B 21/02* (2013.01); *F25D 2400/10* (2013.01)

(58) **Field of Classification Search**
CPC F25B 21/02; F25D 2400/12
USPC 62/3.3, 3.6, 3.62, 3.7, 457.1, 371, 530; 165/104.33
See application file for complete search history.

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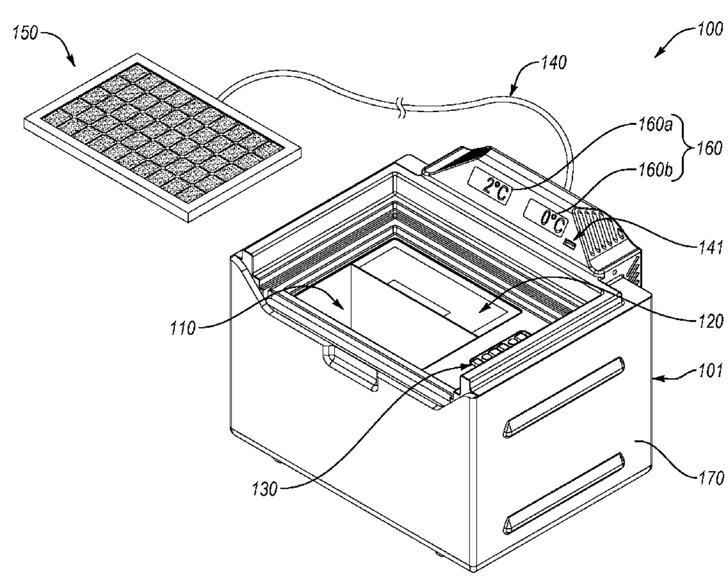
(57) **ABSTRACT**

Embodiments disclosed herein relate to apparatuses and methods for storing temperature-sensitive items. More specifically, embodiments include a storage apparatus that may store the temperature-sensitive items. For example, the storage apparatus may include a storage compartment that may be maintained at a predetermined temperature or temperature range.

48 Claims, 10 Drawing Sheets



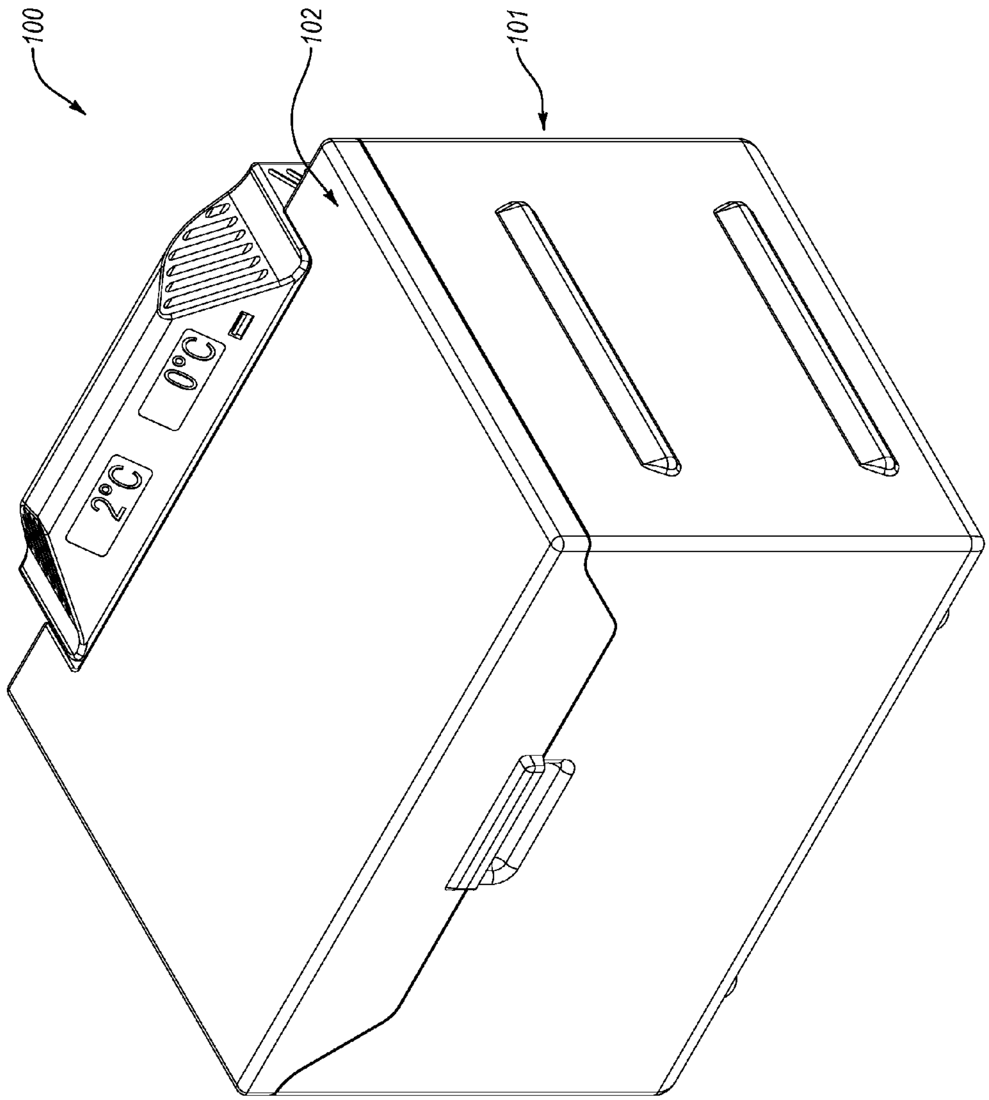
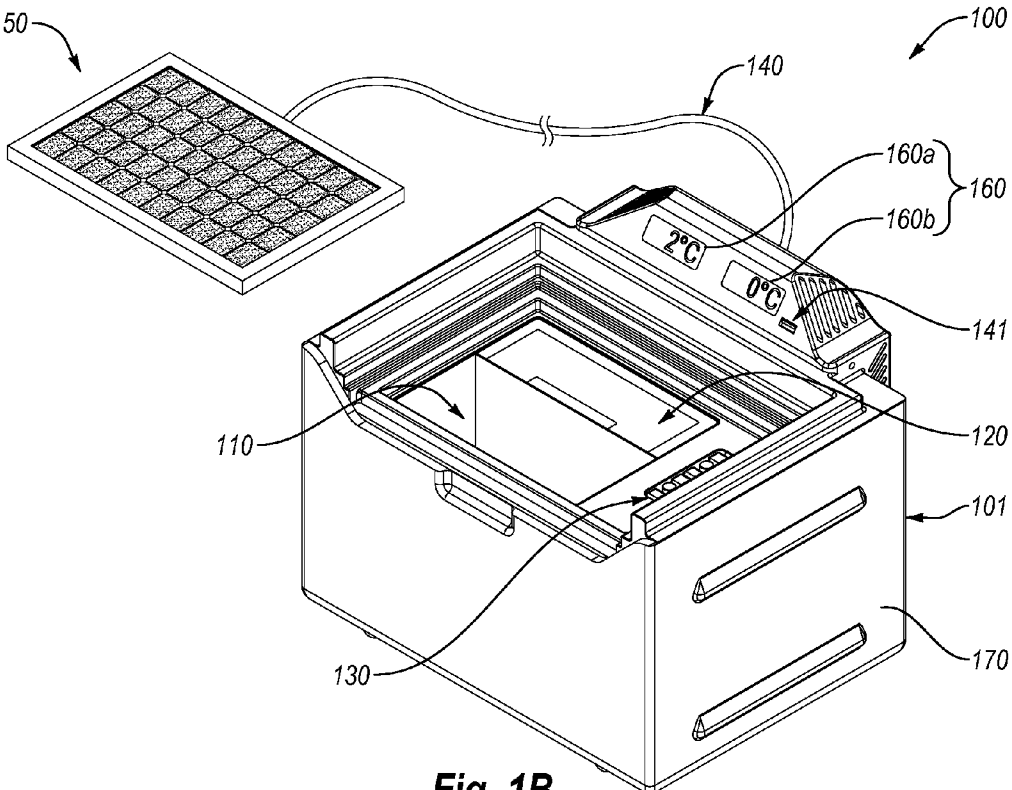


Fig. 1A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100
140
160a
160
160b
2°C
0°C
141
110
120
101
130
170

Fig. 1B

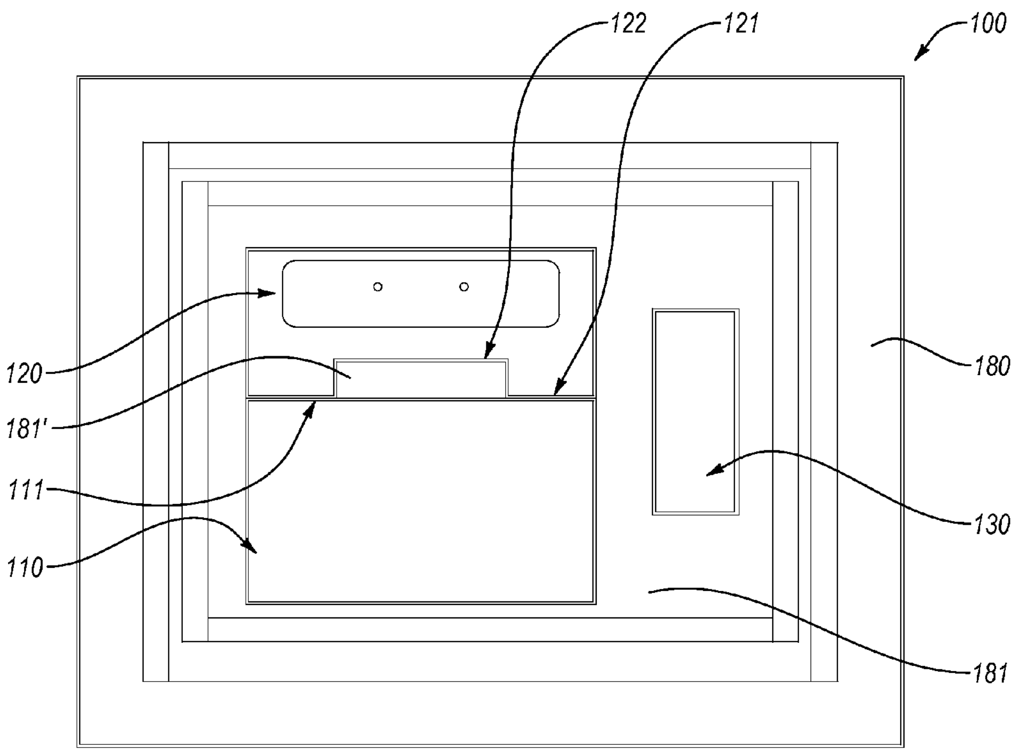
122
121
100
120
181'
111
110
180
130
181

Fig. 1C

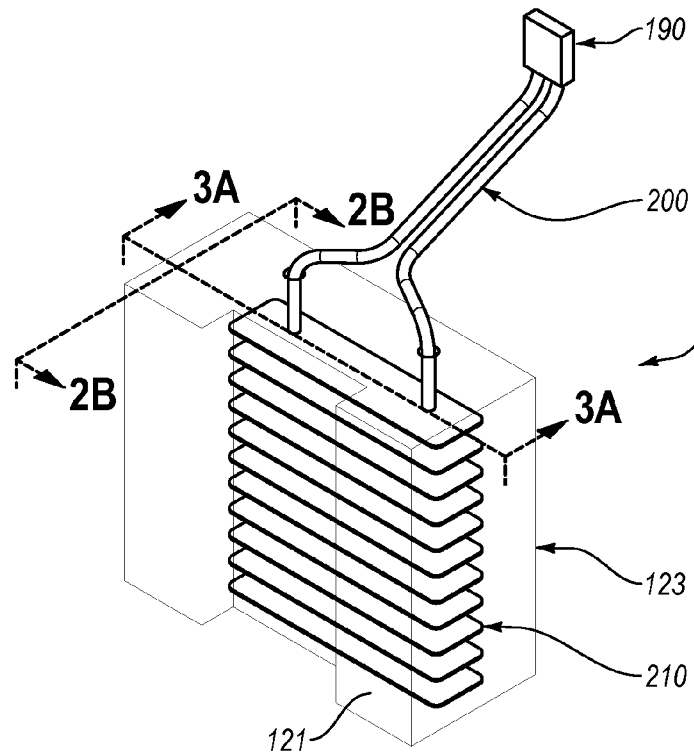

Fig. 2A

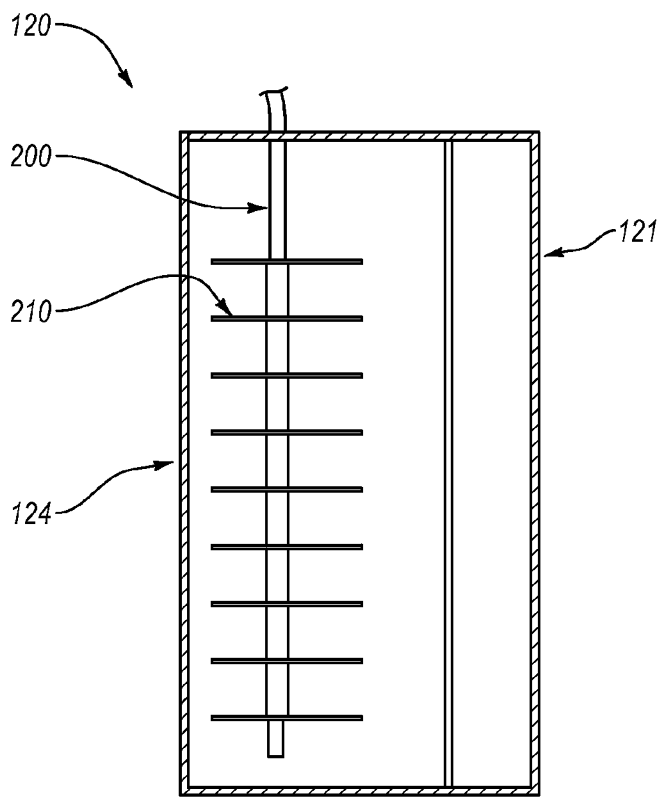

Fig. 2B

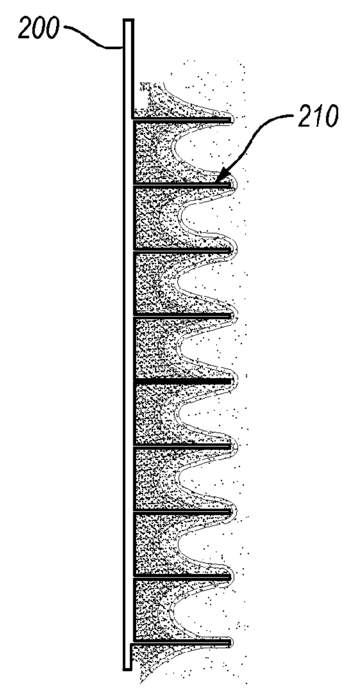

Fig. 2C

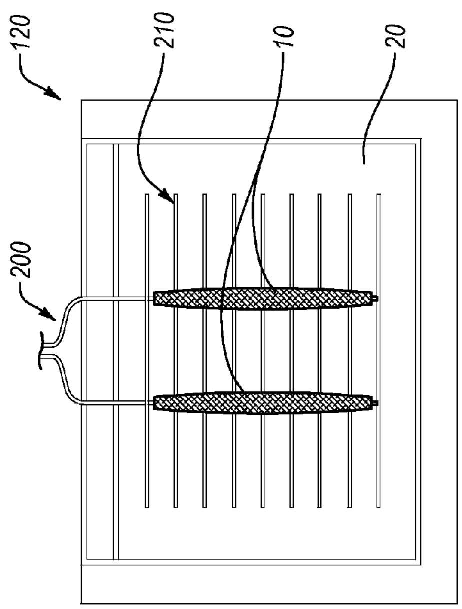

Fig. 3A

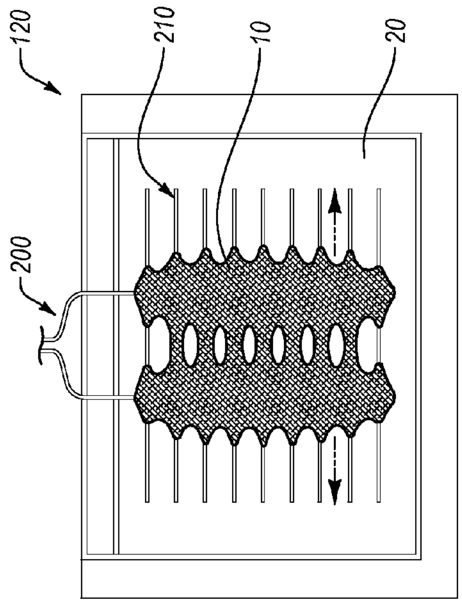

Fig. 3B

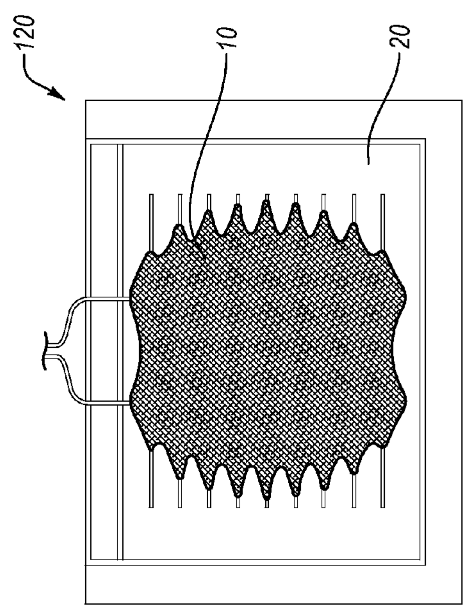

Fig. 3C

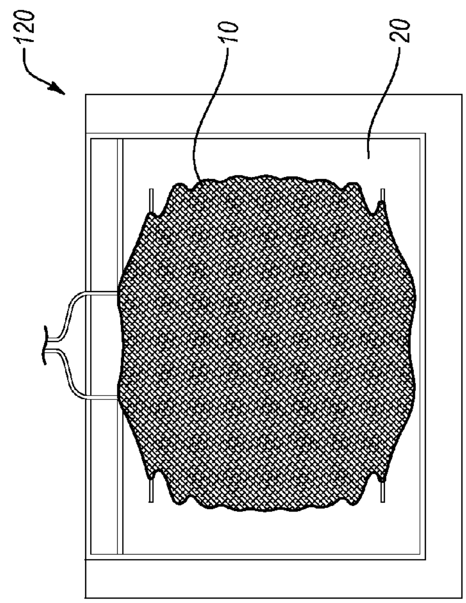

Fig. 3D

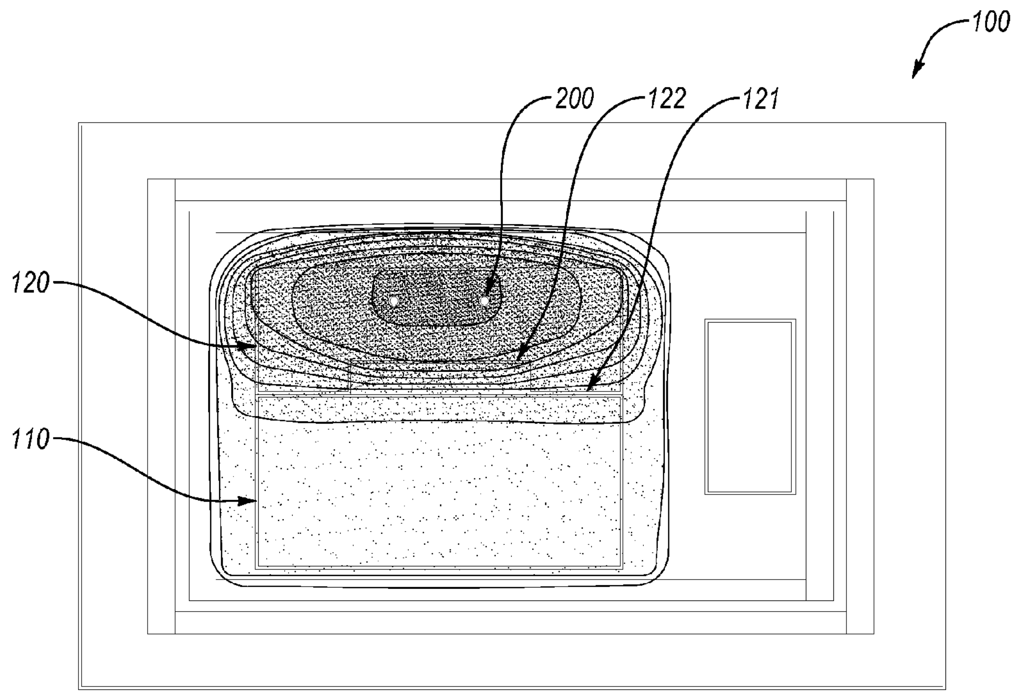

Fig. 4

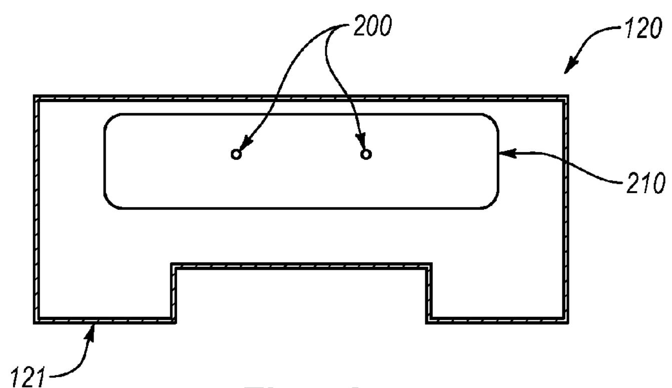

Fig. 5A

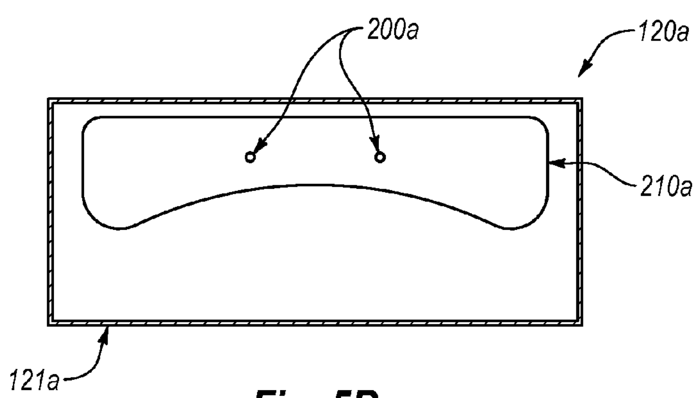

Fig. 5B

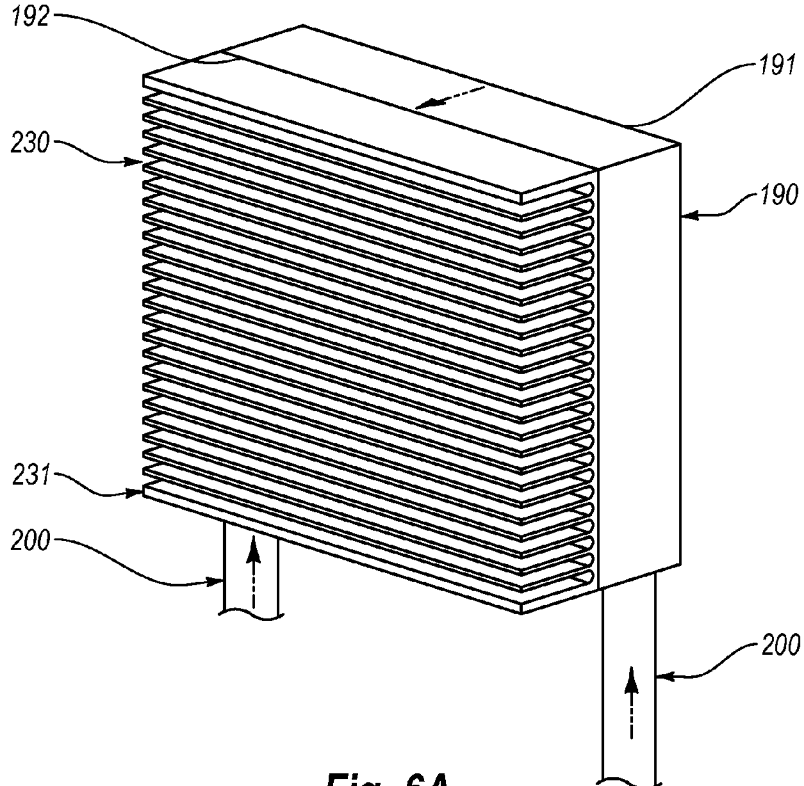

Fig. 6A

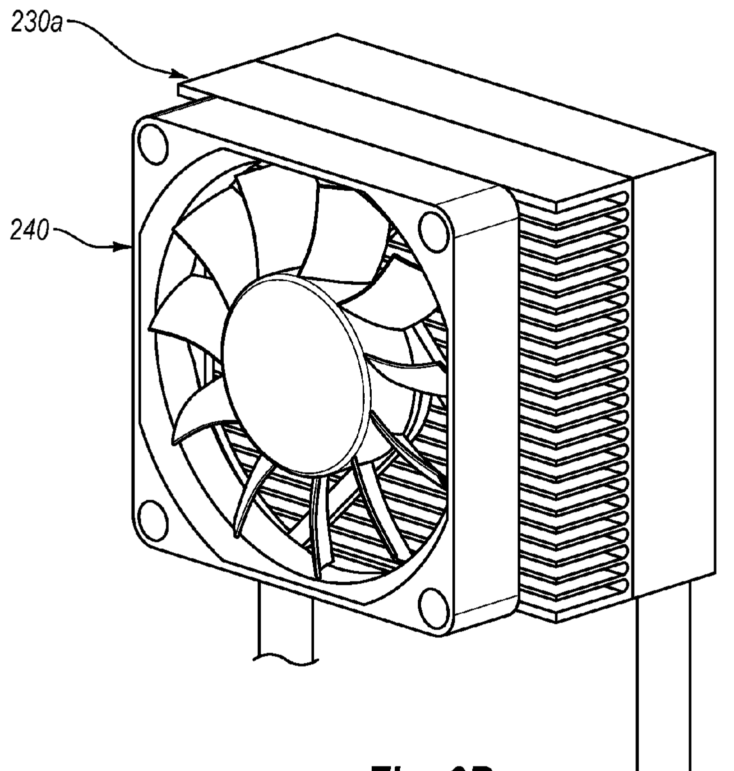

Fig. 6B

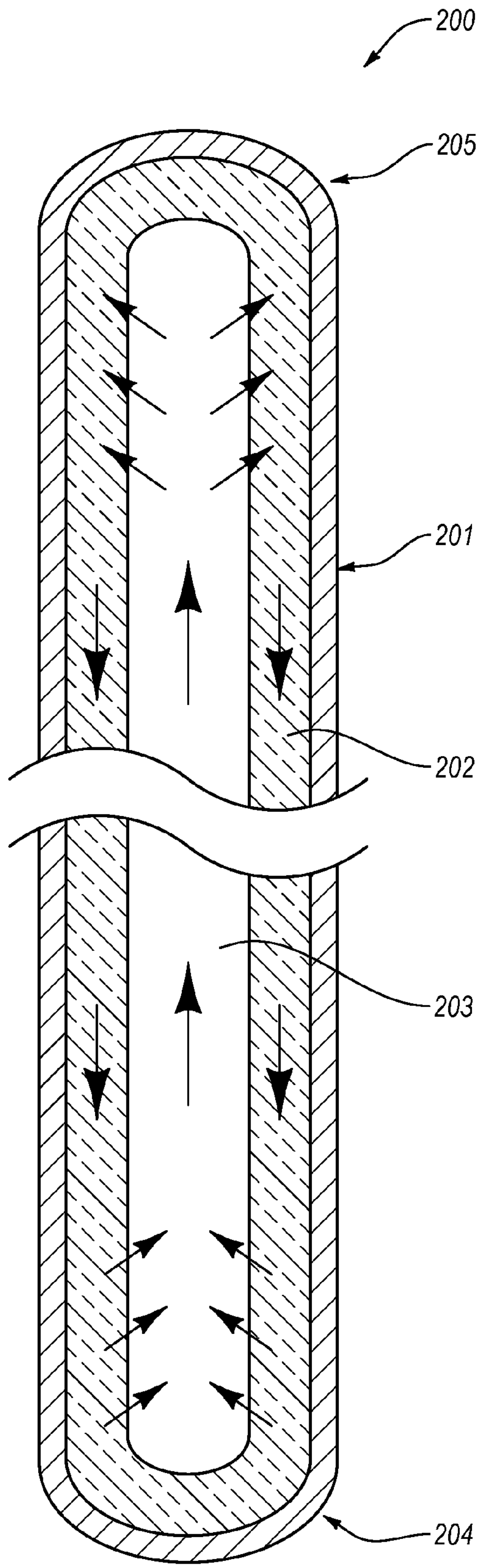

Fig. 7

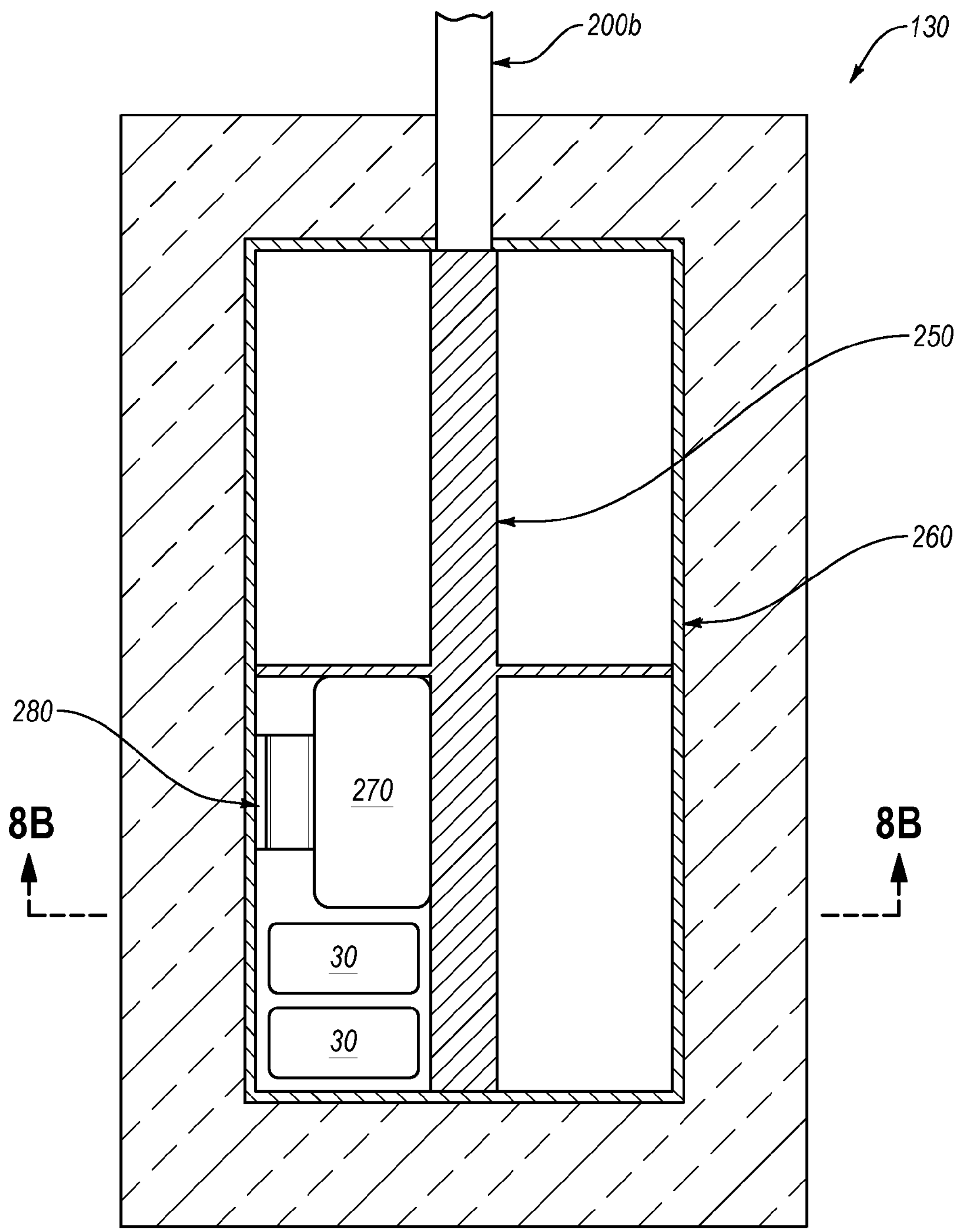

Fig. 8A

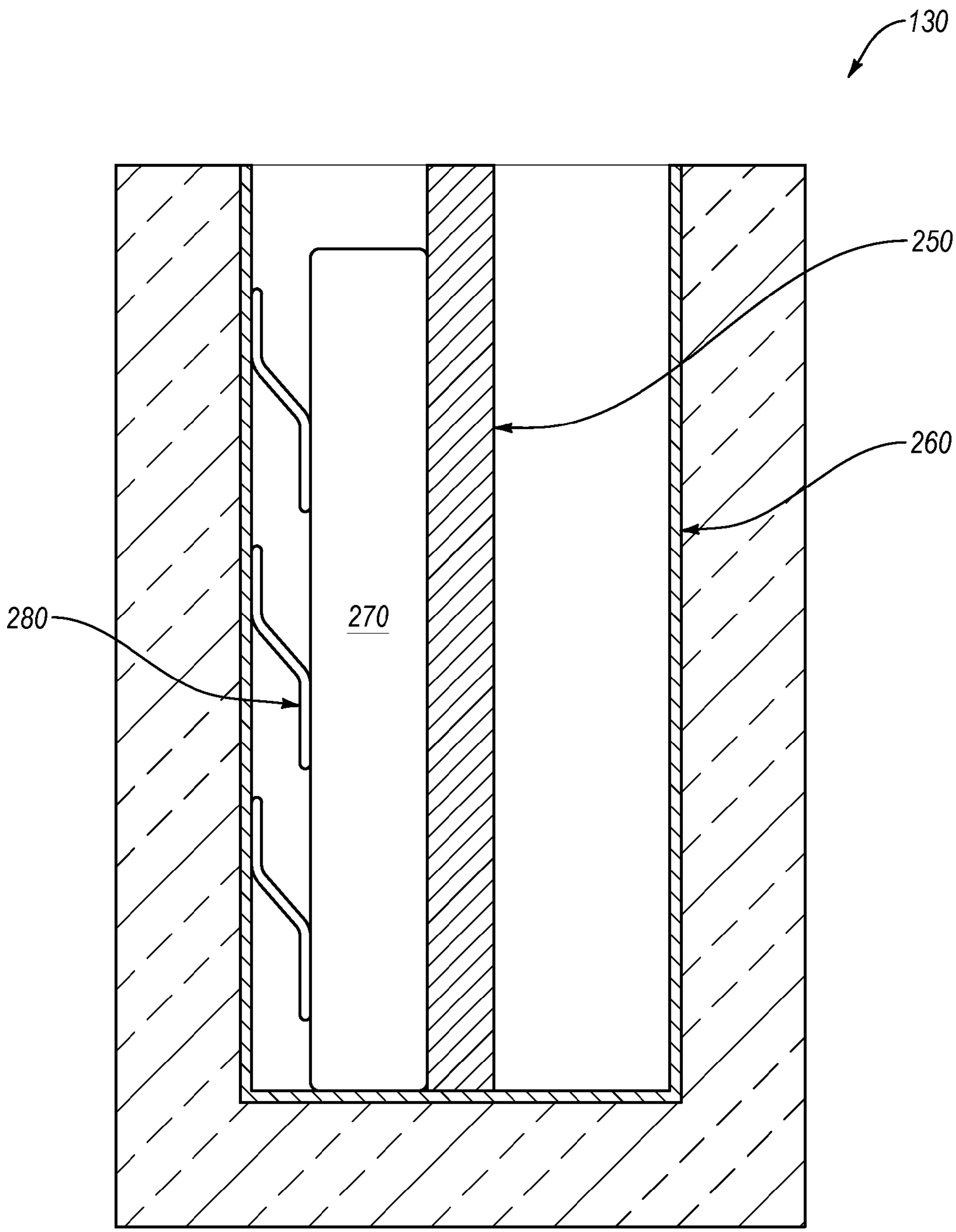

Fig. 8B

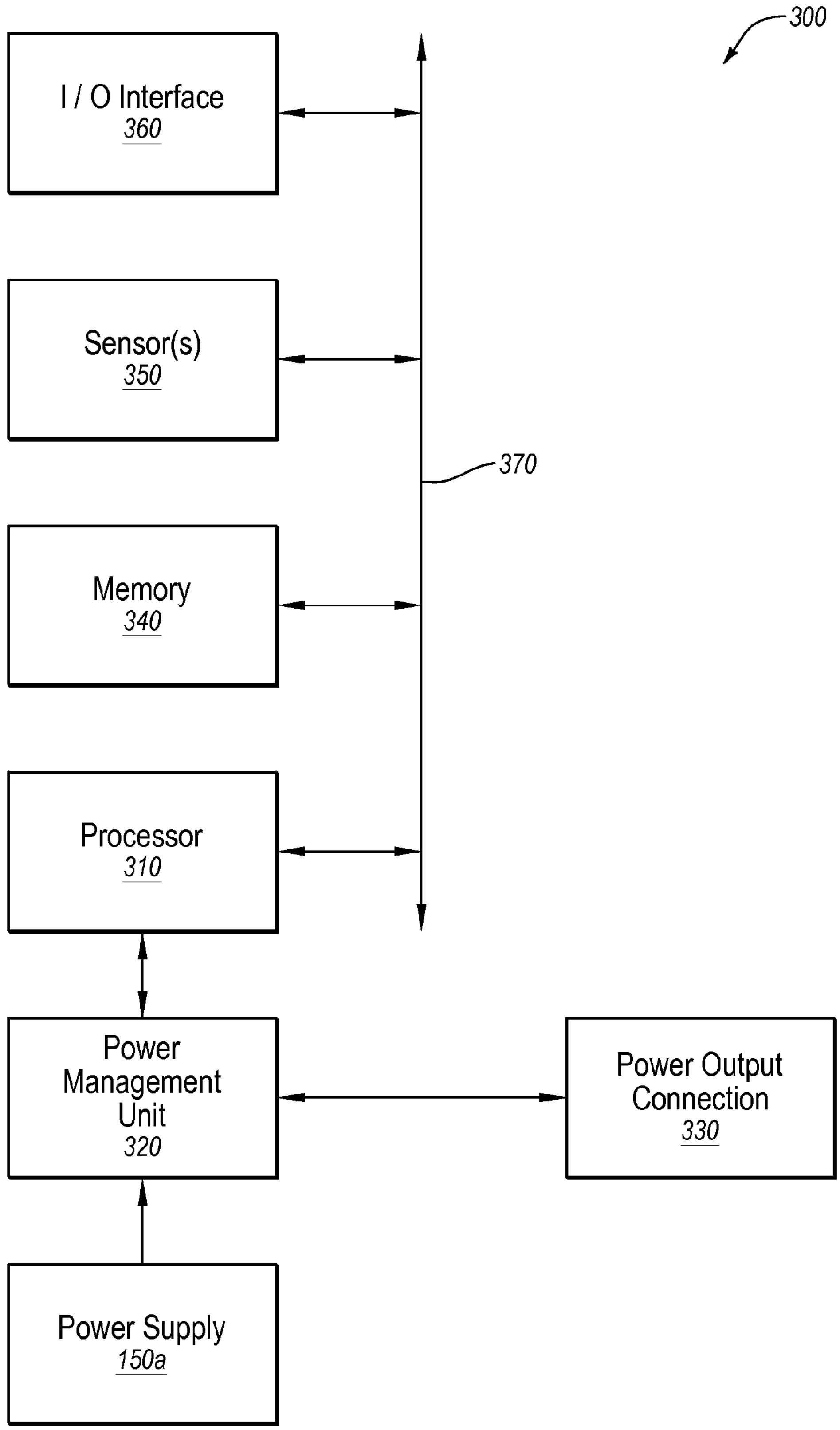
300
I / O Interface
360
Sensor(s)
350
370
Memory
340
Processor
310
Power
Management
Unit
320
Power Output
Connection
330
Power Supply
150a

Fig. 9

STORAGE APPARATUSES AND RELATED METHODS FOR STORING TEMPERATURE-SENSITIVE ITEMS

BACKGROUND

Various materials and substances require storage at a specific temperature or temperature range. For instance, some temperature-sensitive substances or materials may require near-freezing temperature to avoid spoilage. Among others, examples of temperature-sensitive items include pharmaceuticals, biologicals, and food.

Maintaining a near-freezing temperature in some environments may require a temperature-controlled storage space that can be cooled (e.g., relative to the temperature of ambient air). In some instances, cooling the temperature-controlled storage space may require electrical power, which may be drawn from an electrical grid or other main power source. Interruptions in power supply or changes in the environment, such as increase or decrease in temperature of the ambient air may affect the temperature in the temperature-controlled space, which may damage or spoil the temperature-sensitive items.

Thus, manufacturers continue to seek improved devices and methods for storing temperature-sensitive substances.

SUMMARY

Embodiments disclosed herein relate to apparatuses and methods for storing temperature-sensitive items. In an embodiment, a storage apparatus for storing at least one temperature-sensitive material at a controlled temperature is disclosed. The storage apparatus includes an enclosure structure having a storage compartment configured to hold the at least one temperature-sensitive material, and a thermal transfer assembly adjacent to and in thermal communication with the storage compartment. The thermal transfer assembly includes a phase change material disposed therein, one or more heat pipes positioned at least partially within the phase change material, and a plurality of thermally conductive fins in thermal communication with the one or more heat pipes and positioned at least partially within the phase change material. The storage apparatus further includes a thermoelectric heat pump in thermal communication with the one or more heat pipes, a heat sink in thermal communication with the thermoelectric heat pump, and at least one temperature sensor configured to measure temperature in at least one of the storage compartment or the thermal transfer assembly. The storage apparatus also includes a controller operably coupled to the thermoelectric heat pump and to the at least one temperature sensor. The controller is configured to direct the thermoelectric heat pump to controllably cool the phase change material so that a temperature of the storage compartment is controlled responsive to information from the at least one temperature sensor.

In an embodiment, a method of maintaining at least one temperature-sensitive material in a storage apparatus at a temperature lower than an ambient temperature is disclosed. The method includes placing the at least one temperature-sensitive material in a storage compartment of the storage apparatus that is adjacent to and in thermal communication with a thermal transfer assembly of the storage apparatus having a phase change material disposed therein. The method further includes controllably changing a phase of a portion of the phase change material by removing heat therefrom via one or more heat pipes attached to a thermoelectric heat pump so that a first portion of the phase change material is in a solid phase and a second portion of the phase change material is in a liquid phase that is disposed between the storage compartment and the first portion.

The foregoing summary is illustrative only and is not intended to be in any way limiting. In addition to the illustrative aspects, embodiments, and features described above, further aspects, embodiments, and features will become apparent by reference to the drawings and the following detailed description.

BRIEF DESCRIPTION OF THE FIGURES

FIG. **1**A is an isometric view of a storage apparatus with a closed lid according to an embodiment.

FIG. **1**B is an isometric view of a storage apparatus without the lid and connected to a power source according to an embodiment.

FIG. **1**C is a partial top view of the storage apparatus of FIG. **1**B.

FIG. **2**A is an isometric view of a thermal transfer assembly of a storage apparatus according to an embodiment.

FIG. **2**B is a cross-sectional view of the thermal transfer assembly of FIG. **2**A.

FIG. **2**C is a schematic illustration of a temperature profile near a heat pipe and fins of the thermal transfer assembly of FIG. **2**B.

FIG. **3**A is a schematic of a stage of solidification process of a phase change material in the thermal transfer assembly according to an embodiment.

FIG. **3**B is a schematic of another stage of solidification process of the phase change material in the thermal transfer assembly according to an embodiment.

FIG. **3**C is a schematic of yet another stage of solidification process of the phase change material in the thermal transfer assembly according to an embodiment.

FIG. **3**D is a schematic of still another stage of solidification process of the phase change material in the thermal transfer assembly according to an embodiment.

FIG. **4** is a schematic of a temperature profile in a thermal transfer assembly and in a storage compartment of a storage apparatus according to an embodiment.

FIG. **5**A is a top, cross-sectional view of a thermal transfer assembly according to an embodiment.

FIG. **5**B is a top, cross-sectional view of a thermal transfer assembly according to another embodiment.

FIG. **6**A is an isometric view of a heat pump with a heat sink of a storage apparatus according to an embodiment.

FIG. **6**B is an isometric view of a heat pump with a heat sink of a storage apparatus according to another embodiment.

FIG. **7** is a cross-sectional view of a heat pipe of a storage apparatus according to an embodiment.

FIG. **8**A is a top, cross-sectional view of a freezer compartment of a storage apparatus according to an embodiment.

FIG. **8**B is a side cross-sectional view of the freezer compartment of FIG. **8**A.

FIG. **9** is a block diagram of a controller of a storage apparatus according to an embodiment.

DETAILED DESCRIPTION

In the following detailed description, reference is made to the accompanying drawings, which form a part hereof. In the drawings, similar symbols typically identify similar components, unless context dictates otherwise. The illustrative embodiments described in the detailed description, drawings, and claims are not meant to be limiting. Other embodiments may be utilized, and other changes may be made, without departing from the spirit or scope of the subject matter presented here.

Embodiments disclosed herein relate to apparatuses and methods for storing temperature-sensitive items. More specifically, at least some embodiments include a storage apparatus that may store the temperature-sensitive items. For example, the storage apparatus may include a storage compartment that may be maintained at a predetermined temperature or temperature range. In some embodiments, the temperature in the storage compartment may be lower than the temperature outside of the storage apparatus or ambient temperature. As such, the storage apparatus may store temperature-sensitive items at a lower temperature than the ambient temperature.

In some embodiments, the storage apparatus may maintain the storage compartment at approximately the same temperature or approximately within the same temperature range in the absence of external supply of electrical power. For instance, the storage compartment may be maintained at a predetermined temperature for one or more days without external power supply (e.g., 1 to 3 days). Accordingly, the storage apparatus may be deployed in locations or applications that may lack a reliable or constant supply of electrical power (e.g., away from an electrical grid).

FIGS. **1A-1C** illustrate an embodiment of a storage apparatus **100**. As described below in more detail, the storage apparatus **100** may include one or more storage compartments, which may be maintained at a predetermined temperature or temperature range. In some embodiments, the storage apparatus **100** may include a main housing **101** and a lid **102**, as illustrated in FIG. **1**A. In some instances, the lid **102** may be removably attached to the main housing **101**. In other words, the lid **102** may be completely removed from the main housing **101** to provide access to the compartments located in the main housing **101**. Conversely, the lid **102** may be reattached to the main housing **101** to close the compartments located in the main housing **101**.

It should be appreciated that, generally, the lid **102** may be attached to the main housing **101** with any number of suitable mechanisms. For instance, the lid **102** may be connected to the main housing with one or more hinges. Also, the lid **102** may be slidingly or otherwise attached to the main housing **101**, in a manner that movement or rotation of the lid **102** may open and close access to the storage compartments in the main housing **101**. In any event, however, the lid **102** may be attached to the main housing in a manner that may selectively provide access to the compartments of the storage apparatus **100**.

As mentioned above, the storage apparatus **100** may include one or more compartments (e.g., compartments for storing temperature-sensitive items). In particular, in an embodiment illustrated in FIG. 1B, the main housing **101** of the storage apparatus **100** includes a storage compartment **110** and a thermal transfer assembly **120**, which may cool the storage compartment **110** to a suitable or predetermined temperature. Moreover, the thermal transfer assembly **120** may maintain the storage compartment **110** at a suitable or predetermined temperature or temperature range. In some embodiments, the thermal transfer assembly **120** may maintain the storage compartment **110** at a near-freezing temperature, as described below in further detail.

In the illustrated embodiment, the storage apparatus **100** may include a freezer compartment **130** located in the main housing **101**, which may be maintained at or below freezing temperature (e.g., at or below 0° C.). However, in other embodiments, the freezer compartment **130** may be omitted. In an embodiment, the freezer compartment **130** may store items that may require temperature of below 0° C. to avoid spoliation. In an embodiment, the freezer compartment **130** may store items that may require temperature of below 0° C. and above −25° C. to maintain quality. In an embodiment, the freezer compartment **130** may freeze ice, or WHO-approved medical ice packs, to a temperature below 0° C. and above −10° C. Moreover, similar to the storage compartment **110**, the freezer compartment **130** may maintain the temperature therein at predetermined level or range in the absence of electrical power.

To cool or maintain a predetermined temperature in the thermal transfer assembly **120** or freezer compartment **130**, the storage apparatus **100** may be coupled to an electrical power source. For example, the storage apparatus **100** may include an electrical connection **140** that may electrically couple the storage apparatus **100** to the electrical power source. In an embodiment, the power source may supply power to one or more heat pumps that may regulate the temperature in the storage compartment **110** or the freezer compartment **130**, as described below.

The particular source of power may vary from one embodiment to the next, and may include an alternating or direct current sources. In an embodiment, the storage apparatus **100** may connect to a power source **150** that may supply direct current power thereto. For instance, the power source **150** may be a solar panel, a battery (e.g., a rechargeable battery), or the like as well as combinations of such power supplies. For example, the storage apparatus may be electrically coupled to a solar panel that may produce 100-160 W of direct current power.

Hence, in an embodiment, the storage apparatus **100** may accept direct current power. In an embodiment, the storage apparatus **100** may connect to a power source that may provide alternating current, such as a generator, a main power grid, or the like. As such, the storage apparatus **100** may operate from direct or alternating current.

Additionally or alternatively, the storage apparatus **100** may include a power inverter to convert direct current to alternating current, and may operate on alternating current. Conversely, the storage apparatus **100** may include a rectifier to convert alternating current to direct current and may operate on direct current. Consequently, in an embodiment, the storage apparatus **100** may accept direct and alternating current for operation thereof and may be connected to a power source that provides either direct or alternating current.

In an embodiment, the storage apparatus **100** also may include an auxiliary power supply port. More specifically, the storage apparatus **100** may receive or dispense power via the auxiliary power supply port. For instance, the storage apparatus **100** may include a Universal Serial Bus (USB) port **141**. The USB port **141** may supply power to auxiliary devices, such as mobile phones. In an embodiment, the USB port **141** may be configured to receive power (e.g., to charge an optional battery).

While the storage apparatus **100** may include any of the storage compartment **110**, thermal transfer assembly **120**, or freezer compartment **130**, in some embodiments, the storage apparatus **100** may include only a single compartment or dual compartments. For instance, the storage apparatus **100** may include only the freezer compartment **130**. Also optionally, the storage compartment **110** and thermal transfer assembly **120** may be integrated together in a manner to form a single storage compartment that may maintain temperature-sensitive items at a suitable temperature or temperature range.

As described below in further detail, the storage apparatus **100** may include a controller that may monitor the temperature in one or more of the storage compartment **110**, thermal transfer assembly **120**, or freezer compartment **130** and may direct a heat pump on and off time or heat exchange production thereof. Additionally, the storage apparatus **100** may include one or more displays, which may provide visual information about the temperature in the storage compartment **110**, thermal transfer assembly **120**, freezer compartment **130**, or combinations thereof. For instance, the storage apparatus **100** may include displays **160**, such as displays **160***a*, **160***b*, which may show temperature readings from the storage compartment **110** and freezer compartment **130**, respectively.

Thus, for example, a user may monitor the temperature readings from the storage compartment **110** or freezer compartment **130**. More specifically, as the power supply becomes unavailable to the storage apparatus **100**, the user may monitor the displays **160** to make sure that the temperature in the storage compartment **110** or freezer compartment **130** remains at suitable levels. Moreover, in addition to or in lieu of the displays **160**, the storage apparatus **100** may include an audible monitor that may provide an audible alter if the temperature in any of the storage compartment **110**, thermal transfer assembly **120**, or freezer compartment **130** falls below a suitable level, which may be preset (e.g., by a user, by a manufacturer, by a supplier of temperature-sensitive items, etc.). The displays **160** also may optionally provide an alert if the storage apparatus **100** stops receiving power from a power source.

In an embodiment, the main housing **101** also may include an outer shell **170**. For example, the storage compartment **110** or the thermal transfer assembly **120** may be positioned within an outer shell **170**, which may secure or protect the storage compartment **110** and the thermal transfer assembly **120**. For instance, among other things, the outer shell **170** may protect the storage compartment **110** or the thermal transfer assembly **120** from impact, from environmental effects or conditions, such as debris, dust, and liquids. The outer shell **170** may include any suitable material, which may vary from one embodiment to another. In some instances, the outer shell **170** may include polycarbonate, nylon, fiberglass, or the like. Moreover, the outer shell **170** may include thermally insulating material (e.g., thermoplastic material), which may at least partially insulate the storage compartment **110**, thermal transfer assembly **120**, freezer compartment **130**, or combinations thereof.

The lid **102** (FIG. **1**A) may include the same or similar material as the outer shell **170** of the main housing **101**. Furthermore, the lid **102** (FIG. **1**A) may include an outer shell comprising the same or similar material as the outer shell **170**, which may at least partially encapsulate thermally insulating material of the lid (e.g., polyurethane foam or the like). In any event, the materials comprising the lid **102** (FIG. **1**A) and the outer shell **170** and configurations thereof (e.g., thicknesses, shapes, such as ribs and other stiffening features, etc.) may provide sufficient structural rigidity and strength to the main housing **101** and the lid.

Likewise, the main housing **101** may include thermally insulating material that may at least partially surround or encapsulate one or more of the storage compartment **110**, thermal transfer assembly **120**, or freezer compartment **130**. As shown in FIG. **1**C, any of the storage compartment **110**, thermal transfer assembly **120**, or freezer compartment **130** may be at least partially surrounded by insulation, such as thermal insulation **180**. The thermal insulation **180** may reduce heat exchange between the storage compartment **110**, thermal transfer assembly **120**, or freezer compartment **130** and the environment outside of the storage apparatus **100**, such as ambient air.

Suitable thermal insulation **180** may change from one embodiment to another, and may depend, among other things, on the intended or anticipated outside environment. Suitable materials for the thermal insulation **180** include but are not limited to foam, such as polyurethane foam, blocks with low thermal conductivity medium (e.g., gas, liquid, semi-liquid, or solid, which may include xenon, argon, air, polystyrene, alumina, asbestos, etc.). The thermal insulation **180** also may include high performance insulation such as vacuum blocks, aerogel, or other materials or structures that may have thermal conductivity that is less than thermal conductivity of blown polyurethane (e.g., less than 0.3 W/m/K).

In an embodiment, the storage apparatus **100** also may include thermal insulation between at least some of the storage compartment **110**, thermal transfer assembly **120**, or freezer compartment **130**. For example, thermal insulation **181** may at least partially surround one or more of the storage compartment **110**, thermal transfer assembly **120**, or freezer compartment **130**. In an embodiment, the freezer compartment **130** may be adjacent to the storage compartment **110** and to the thermal transfer assembly **120** (e.g., the freezer compartment **130** may be separated from the storage compartment **110** and thermal transfer assembly **120** by a wall, such as a wall formed by the thermal insulation **181**). The thermal insulation **181** may facilitate the storage compartment **110**, thermal transfer assembly **120**, and freezer compartment **130** with different temperatures therein one from another. In other words, the thermal insulation **181** may impede or prevent conductive heat transfer between the storage compartment **110**, thermal transfer assembly **120**, and freezer compartment **130**, thereby facilitating different temperatures therein.

In some instances, the storage compartment **110**, thermal transfer assembly **120**, or freezer compartment **130** may include only partial insulation therebetween. In particular, in an embodiment, at least a portion of one of the storage compartment **110**, thermal transfer assembly **120**, or freezer compartment **130** may be in thermal contact with at least a portion of another of the storage compartment **110**, thermal transfer assembly **120**, or freezer compartment **130**. For example, the storage compartment **110** and thermal transfer assembly **120** may include thermal insulation **181'** therebetween, which may span partially along a heat transfer side **121** of the thermal transfer assembly **120**. As such, a portion of the heat transfer side **121** may be in direct contact with a portion of a first side **111** of the storage compartment **110**, while another portion of the heat transfer side **121** may be insulated from the storage compartment **110**.

In an embodiment, the thermal transfer assembly **120** may have one or more thermally conductive walls that may define the heat transfer side **121**. Also, the heat transfer side **121** may optionally include a recess **122** that may have thermal insulation **181'** therein. Accordingly, a portion of the heat transfer side **121** may be separated or insulated from the first side **111** of the storage compartment **110**.

In addition, for example, the thermal transfer assembly **120** may include one or more additional walls that, together with the heat transfer side **121** may form or define the perimeter of the thermal transfer assembly **120**. In an embodiment, the walls collective may define an approximately rectangular perimeter. It should be appreciated that the shape and size of the thermal transfer assembly **120** may vary from one embodiment to the next. Hence, the thermal transfer assembly **120** may have a circular, triangular, polygonal, or other suitable perimeters. Accordingly, the heat transfer side of the thermal transfer assembly may have any suitable shape and may be formed by a section or a portion of a single wall or multiple walls that define a perimeter of the thermal transfer assembly.

In an embodiment, the thermal insulation **181'** or the recess **122** may be positioned along a mid-portion of the heat transfer side **121**. As such, opposing ends of the heat transfer side **121** may be in contact with the first side **111** of the storage compartment **110**. It should be appreciated that the thermal insulation **181'** may include any suitable material or structure, which may be similar to or the same as the materials or structures described above in connection with the thermal insulation **180**. Furthermore, in some embodiments, the partial separation between the recess **122** of the heat transfer side **121** and the first side **111** of the storage compartment **110** may provide insulation therebetween.

As described above, in an embodiment, the storage compartment **110** may include the first side **111** that may be in thermal communication with the heat transfer side **121** of the thermal transfer assembly **120**. In some embodiments, the first side **111** may include thermally conductive material. For example, the first side **111** may be formed by a thermally conductive wall.

Moreover, the perimeter of the storage compartment **110** may be at least in part defined by the first side **111**. For instance, the perimeter of the storage compartment **110** may be defined collectively by the first side **111** and by additional one or more walls that may be thermally conductive or thermally insulating. In some instances, the storage compartment **110** may have an approximately rectangular perimeter. Generally, the storage compartment **110** may have any suitable shape. Also, in an embodiment, the first side **111** of the storage compartment may have a shape that corresponds with the shape of the heat transfer side **121** of thermal transfer assembly.

In any event, however, while the perimeter of the storage compartment **110** may vary from one embodiment to the next, the perimeter may in part define a volume of the storage compartment **110** that is suitable for housing temperature-sensitive materials, as described above. For example, the volume of the storage compartment **110** may be between 2 and 15 liters. Also, as described above, the first side **111** of the storage compartment **110** may be in thermal communication with at least a portion of the heat transfer side **121** of the thermal transfer assembly **120**. Accordingly, removing heat and lowering the temperature in the thermal transfer assembly **120** also may remove the heat from and lower the temperature in the storage compartment **110**.

Moreover, as described below in more detail, the recess **122** or the thermal insulation **181'** may facilitate a substantially even temperature distribution along the first side **111** of the storage compartment **110**. In other words, the recess **122** or the thermal insulation **181'** may facilitate a controlled temperature selection and distribution on the first side **111** of the storage compartment **110**. For example, the storage apparatus **100** may maintain the first side **111** of the storage compartment **110** at near-freezing temperature. In some embodiments, the storage apparatus **100** may maintain the first side **111** at a temperature in one or more of the following ranges: between about 8° C. and about 2° C.; about 8° C. and about 5° C.; between about 4° C. and about 2° C.; or between about 3° C. and about 0° C. In some instances, the temperature of the first side **111** of the storage compartment **110** may be less than 0° C. or greater than 8° C.

Also, the recess **122** or the thermal insulation **181'** may prevent the temperature of the first side **111** from falling below a predetermined temperature (e.g., below 0° C., or below 2° C.) by at least partially impeding heat transfer from the storage compartment **110** to the thermal transfer assembly **120**. In any event, the storage apparatus **100** may have a predetermined temperature or temperature range at the first side **111** of the storage compartment **110**.

The temperature in the storage compartment **110** may, at least in part, depend on the temperature of the first side **111** thereof. For instance, heat in the storage compartment **110** may be transferred to the first side **111** and may be subsequently transferred to the thermal transfer assembly **120** and further removed therefrom, as described below. Accordingly, maintaining temperature of the first side **111** at predetermined level or range, such as at about 2° C., also may approximately maintain the temperature inside the storage compartment **110** at a predetermined level or within a predetermined range, which may be the same as or similar to the temperature of the first side **111**.

As mentioned above, in some instances, temperature-sensitive items may require storage at near but not below freezing temperature to avoid damage or spoilage thereof. Hence, maintaining a near-freezing but not below freezing temperature may facilitate safe storage of temperature-sensitive materials in the storage compartment **110**. Moreover, in some embodiments, the storage apparatus **100** may maintain the temperature inside the storage compartment **110** approximately at a predetermined level in the absence of power supply to the storage apparatus **100**. For example, the thermal transfer assembly **120** may provide and maintain an approximately constant temperature or a temperature range (e.g., between 0° C. and 8° C.) for a period of at least 3 days, with ambient temperature outside of the storage apparatus at about 43° C.

For instance, as illustrated in FIG. **2A**, the thermal transfer assembly **120** may include an enclosure **123**, which may be at least partially formed by the heat transfer side **121**. The enclosure **123** may house a phase change material (PCM), which may be at least partially frozen by a heat pump **190**. Suitable PCM may vary from one embodiment to the next and may include water, PureTemp 1 (from Entropy Solutions, Inc.), or the like.

In some instances, the enclosure **123** may be sealed, such that the PCM may not be readily accessible (e.g., the enclosure **123** may include welded seams). Alternatively, the enclosure **123** may seal the PCM therein in a manner that removing one or more portions of the enclosure may provide access to the PCM. As such, the PCM may be added or at least partially removed or replaced.

In an embodiment, the heat pump **190** may remove heat from the PCM, thereby changing the phase of the PCM (e.g., from liquid to solid phase). Also, as the PCM is cooled, the PCM may cool the heat transfer side **121** of the thermal transfer assembly **120**. It should be appreciated that the specific volume of the enclosure and of the PCM may vary from one embodiment to the next and may depend, among other things, on the size of the storage compartment, number or volume of the temperature-sensitive items stored in the storage compartment, expected ambient temperature during operation, or the like.

In some embodiments, the heat pump **190** may be in thermal communication with the PCM through one or more heat pipes, such as through heat pipes **200**, which may transfer heat from the PCM to the heat pump **190**. More specifically, the heat pump **190** may cool a first end of the heat pipes **200**, thereby creating a temperature differential between the first end (i.e., the end coupled to the heat pump **190**) and a second end, which may be positioned within the PCM.

As described below, the heat pipes **200** may transfer heat from high-temperature end thereof to the low-temperature end thereof. As such, the heat pipes **200** may transfer heat from the PCM to the heat pump **190**. In turn, the heat pump **190** may maintain the first end of the heat pipes **200** at a temperature that is lower than the temperature of the second end of the heat pipes **200**, thereby facilitating heat transfer from the PCM to the heat pump **190**.

Also, the heat pipes **200** may include one or more bends therein, which may facilitate placing the heat pump **190** at a suitable location on the storage apparatus. For example, the heat pump **190** may be located at a back side of the storage apparatus, such that the heat pump **190** is at least partially concealed from a user of the storage apparatus. Alternatively, the heat pipes **200** may be approximately linear. In any event, the heat pipes **200** may transfer heat from the PCM to the heat pump **190**.

In an embodiment, the thermal transfer assembly **120** also may include one or more fins in thermal communication with the heat pipes **200**. For example, the thermal transfer assembly **120** may include a plurality of thermally conductive fins **210** attached to or in thermal communication with the heat pipes **200**. The fins **210** may increase heat transfer rate from the PCM to the heat pipes **200** and to the heat pump **190**. Moreover, the heat pipes **200** may facilitate directional freezing of the PCM, as described below.

The fins **210** may have any number of suitable shapes and sizes. In an embodiment, the fins **210** may be approximately planar and may have substantially flat opposing surfaces, with the fins **210** oriented substantially horizontally. Alternatively or additionally, at least some of the fins may be bent, wavelike, or may have irregular shapes. In addition, the fins **210** may include any number of suitable thermally conductive materials and combinations thereof. Examples of suitable materials for the fins **210** include, but are not limited to, aluminum, copper, or alloys thereof.

The particular heat pump **190** may vary from one embodiment to the next. In some embodiments, the heat pump **190** may be a thermoelectric heat pump, such as a Peltier cell. As described below in more detail, the thermoelectric heat pump **190** may be controlled by a controller that may be operably coupled to the heat pump **190**. In any event, the heat pump **190** may remove heat from the storage compartment **110**, and such heat removal may be controlled by the controller.

As shown in FIG. **2**B, in an embodiment, the heat pipes **200** and the fins **210** may be positioned near a back side **124** of the thermal transfer assembly **120**. Hence, in some instances, the back side **124** may be cooler than the heat transfer side **121** of the thermal transfer assembly **120**. For example, the back side **124** may be cooled to below freezing temperature, while the heat transfer side **121** may remain above the freezing temperature (e.g., at about 2° C.). Moreover, in an embodiment, most of the PCM may be frozen before the storage compartment reaches a predetermined temperature (e.g., 2° C.).

For example, as illustrated in FIG. **2**C, the temperature along the fins **210** may increase with distance from the heat pipes **200**. More specifically, FIG. **2**C shows a temperature gradient of the PCM surrounding the heat pipes **200**, with denser stippling that indicates lower temperature zones. In an embodiment, the heat pipes **200** or the fins **210** may be positioned near the back side of the thermal heat transfer assembly. For instance, the heat pipes **200** or fins **210** may be positioned near the back side in a manner that higher temperature zones are closer to the heat transfer side of the thermal heat transfer assembly than to the back side thereof.

As described above, in some embodiments, the PCM that is closer to the heat pipes **200** may freeze. Furthermore, the PCM located father away from the heat pipes **200** may be in a different phase than the heat pipes **200** located near the heat pipes **200**. For instance, the PCM farthest away from the heat pipes **200** may be in a liquid phase. In other words, the PCM near the heat transfer side **121** of the thermal transfer assembly **120** may remain near but above freezing temperature. As such, the thermal transfer assembly **120** may maintain temperature of the storage compartment at a controlled, near-freezing temperature. More specifically, heat transferred from the storage container through the heat transfer side of the thermal transfer assembly and to the PCM near the heat transfer side may be absorbed by the thermal transfer assembly by changing phase of the solid portion(s) of the PCM (e.g., from solid to liquid).

In turn, the heat pump **190** may remove heat from the PCM to maintain at least a portion of the PCM in a phase different than another portion of the PCM (e.g., to maintain most of the PCM in a solid phase). In some instances, the heat pump may continuously maintain a portion of the PCM in a changed phase, such as in a solid phase. In the absence of power from the power source, however, the heat pump may discontinue heat removal from the PCM. Accordingly, for example, the portion of the PCM that is in the solid phase may maintain the temperature of the portion of the PCM that is in a liquid phase at near-freezing by absorbing heat therefrom. In particular, absorbing heat from the PCM that is in a liquid phase may cause at least portion of the solid PCM to change phase to liquid.

In an embodiment, the heat pipes **200** and the fins **210** may facilitate directed or guided phase conversion of the PCM. For instance, the PCM may freeze in a controlled manner and in a controlled direction (e.g., relative to the heat transfer side of the thermal transfer assembly). Likewise, phase change of the solid PCM back to a liquid phase also may occur along direction(s) that are opposite to the direction(s) of freezing of the PCM. Controlled or predictable directions of phase change of the PCM may facilitate maintaining the PCM near the heat transfer side of the thermal transfer assembly at near—but not below—freezing temperature.

In some embodiments, the PCM may preferentially freeze along directions emanating from the heat pipes **200** and along the fins **210**. For example, the PCM may start freezing near the heat pipes **200** (as indicated with denser stippling near the heat pipes **200**, which connotes lower temperature) and proceed along a width of the fins **210** and along a width of the thermal transfer assembly, from the back side to the heat transfer side. Hence, in an embodiment, the PCM may freeze along the width of the thermal transfer assembly and in opposing directions along a length of the thermal transfer assembly. In any event, the shape, size, number, or material of the fins **210**, the specifics and number of the heat pipes **200**, the configuration of the heat pump **190** or power provided thereto, or combinations thereof may vary from one embodiment to the next and may be selected to at least partially control the temperature or freezing profile of the PCM in a manner that a portion of the PCM remains in a liquid phase (e.g., a portion closest to the heat transfer side of thermal transfer assembly), while another portion of the PCM is in a solid phase.

FIGS. 3A-3D illustrate an embodiment of various stages of phase change of the PCM in the thermal transfer assembly **120**. More specifically, FIG. 3A illustrates initial phase change of the PCM, with freezing of the PCM occurring near and about the heat pipes **200**. The freezing profile of the PCM is determined by factors including the material of the fins **210** and the size, shape and relative spacing of the fins **210**. For instance, the thermal transfer assembly **120** may form solid PCM **10** about the heat pipes **200**, and the solid PCM **10** may extend from the heat pipes **200** along and between the fins **210** in a direction of the heat transfer side of the thermal transfer assembly **120** (as shown in FIG. 2C). It should be appreciated that at least some of the PCM may remain in an unchanged phase. For example, the thermal transfer assembly **120** may include liquid PCM **20** that may be in contact or in thermal communication with the solid PCM **10**.

In some embodiments, in an initial state, all of the PCM in the thermal transfer assembly **120** may be liquid PCM **20**. As the heat pump removes heat from the liquid PCM **20**, the thermal transfer assembly **120** may freeze the liquid PCM **20**, thereby converting the liquid PCM **20** to the solid PCM **10**. In an embodiment, as shown in FIG. 3B, the liquid PCM **20** may freeze in opposite directions along the length of the thermal transfer assembly **120**, as indicated by the arrows. For instance, the liquid PCM **20** may freeze near and on the fins **210** in the same or similar direction as the direction along which the fins **210** extend from the heat pipes **200**. In an embodiment, the fins **210** may extend from the heat pipes **200** along the length of the thermal transfer assembly **120**. Accordingly, the liquid PCM **20** may freeze along the fins **210** and in opposing directions oriented along the length of the thermal transfer assembly **120**.

As shown in FIGS. 3C and 3D, the liquid PCM **20** may continue to freeze along the length of the thermal transfer assembly **120**, until a desired amount or volume of the solid PCM **10** is achieved in the thermal transfer assembly **120**. After achieving or maintaining a desired or suitable amount of the solid PCM **10**, the heat pump may at least temporarily stop removing heat from the liquid PCM **20**. Moreover, as the amount of the solid PCM **10** falls below a predetermined level, the heat pump may resume removing heat from the liquid PCM **20**, to reestablish a suitable level of solid PCM **10**. As described below, such operation of the heat pump may be directed by the controller.

In any event, the thermal transfer assembly **120** may provide a near-freezing temperature at the heat transfer side thereof, while maintaining a portion of the PCM as the solid PCM **10**, thereby allowing the solid PCM **10** to absorb heat transferred to the liquid PCM **20** from the storage compartment. FIG. 4 shows an embodiment of a temperature distribution in the storage compartment **110** and in the thermal transfer assembly **120** of the storage apparatus **100**—denser stippling indicates lower temperature, while lighter stippling indicates higher temperature.

As described above, liquid PCM may be in thermal communication with the solid PCM and with the heat transfer side **121** of the thermal transfer assembly **120**. Furthermore, in an embodiment, the liquid PCM may have higher thermal resistance than the solid PCM. Hence, in some instances, the liquid PCM may provide at least partial insulation between the solid PCM and the heat transfer side **121** of the thermal transfer assembly **120**. In any event, the liquid and solid PCM may collectively maintain an approximately constant temperature at the heat transfer side **121**, which may be a near-freezing temperature (e.g., about 0° C. to 2° C.).

For example, the thermal transfer assembly **120** may have a temperature gradient formed by the PCM. In an embodiment, the PCM near the back side **124** of the thermal transfer assembly **120** may have the lowest temperature, as indicated by denser stippling. In some instances, the PCM temperature in the coldest zone may be between about 0° C. and about −3° C. Hence, for instance, if water is used as the PCM, the PCM in the coldest zone may be frozen. It should be appreciated that distinct temperature zone illustrated in FIG. 4 are shown for descriptive purposes only, such as to show an example of approximate temperature distribution within the PCM. Moreover, references to temperature "zones" are not intended to be limiting and refer to temperature of the PCM at a location in the thermal transfer assembly **120**.

Conversely, the PCM near the heat transfer side **121**, the PCM may have the highest temperature. As such, the PCM near the heat transfer side **121** may be in a liquid phase. In some instances, temperature distribution in the PCM may be a continuous gradient, without distinct temperature zones. In any event, in some embodiments, the PCM near the heat transfer side **121** of the thermal transfer assembly **120** may be at near freezing temperature (e.g., at about 2° C.).

Moreover, generally, temperature distribution within the PCM may vary from one embodiment to another. Temperature distribution within the PCM also may vary during operation of the storage apparatus **100**. For instance, if power supply to the storage apparatus **100** is interrupted and the heat pump stops removing heat from the PCM, temperature distribution within the PCM may change. For example, during operation of the heat pump temperature distribution in the PCM may be from the lowest, such as about −3° C. to highest, such as near-freezing temperature (e.g., about 2° C.). If the heat pump stops operating, the lowest temperature in the PCM may change or temperature distribution also may change, such that coldest PCM represents a smaller portion (as compared with the distribution during operation of the heat pump).

In any case, the temperature near the heat transfer side **121** may remain approximately unchanged after the heat pump stops working. In particular, the temperature of the PCM near heat transfer side **121** may stay approximately at a near-freezing temperature for a period of 1 to 3 days. For example, while the heat pump is not removing heat from the PCM, heat absorbed by the PCM near the heat transfer side **121** may be transferred to the colder PCM located farther away from the heat transfer side **121**. As such, the colder zones of the PCM may absorb heat from the zones near the heat transfer side **121** and may maintain the zones near the heat transfer side **121** at near-freezing temperature. Accordingly, the thermal transfer assembly **120** may maintain near-freezing temperature in the storage compartment **110** with interruption of power supply.

In some instances, a greater amount of PCM may freeze near a portion of the thermal transfer assembly **120**. For example, as described above, the thermal transfer assembly **120** may include two heat pipes **200**. Moreover, in some embodiments, the PCM may exhibit greater phase change at a location between the heat pipes **200**. For instance, the solid PCM may form a peak or a dome aligned approximately at a center point between the heat pipes **200**. Also, the solid PCM may be closer to the heat transfer side **121** at the peak of the dome than at other locations in the thermal transfer assembly **120**. In an embodiment, the thermal transfer assembly **120** may include the recess **122**, which may provide additional insulation between the heat transfer side **121** and the storage compartment **110** at location(s) where the solid PCM is unevenly close to the heat transfer side **121**, such as near the peak of the dome formed by the solid PCM.

The width and depth of the recess **122** (i.e., distance from the heat transfer side **121**) may vary from one embodiment to another and may depend, among other things, on temperature distribution in the PCM, location of the dome or peak of the solid phase PCM, type of insulation used in the recess **122** (e.g., using polyurethane foam in the **122** may reduce the thickness thereof as compared with using air). In any event, the depth, length, and insulation material included in the **122** may be chosen in a manner that provides an approximately constant temperature distribution across the interface between the heat transfer side **121** and the storage compartment **110** (e.g., near-freezing temperature).

Moreover, as described above, in some embodiments, the heat pipes **200** may include one or more fins, which may promote phase conversion or freezing/thawing of the PCM along one or more predetermined directions within the thermal transfer assembly **120**. In an embodiment, as illustrated in FIG. **5**A, the thermal transfer assembly **120** may include the fins **210** that may have approximately rectangular shapes. Moreover, the heat pipes **200** or the fins **210** may be positioned near the back side **124** (as compared with the position of the heat pipes **200** and the fins **210** relative to the heat transfer side **121**). Accordingly, the thermal transfer assembly **120** may produce temperature distribution described above.

Also, the heat pipes **200** or the fins **210** may be approximately centered relative to the length of the thermal transfer assembly **120**. For example, ends of the fins **210** may be spaced by approximately the same distances from the opposing sides of the thermal transfer assembly **120**. Hence, in some instances, the PCM may remain in the liquid phase between the ends of the fins **210** and the sides of the thermal transfer assembly **120**. Moreover, as described above, more of the PCM may change to solid phase at a location between the heat pipes **200**, thereby forming a dome or a peak, which may be closer to the heat transfer side **121** than other portions of solid PCM. In some embodiments, however, the fins may have a non-rectangular shape, which may at least partially compensate for such freezing of the PCM, thereby forming solid phase PCM that terminates at approximately the same distance from the heat transfer side **121**.

For example, FIG. **5**B illustrates a thermal transfer assembly **120***a* that may include non-rectangular fins **210***a*. Except as otherwise described herein, the thermal transfer assembly **120***a* and its materials, elements, and components may be similar to or the same as the thermal transfer assembly **120** (FIGS. **1**B-**4**) and its respective materials, elements, and components. For instance, the thermal transfer assembly **120***a* may include heat pipes **200***a* in thermal communication with the thermal transfer assembly **120***a*, which may be similar to or the same as heat pipes **200** (FIGS. **1**B-**4**). In an embodiment, the thermal transfer assembly **120***a* includes fins **210***a* that have a curved or arcuate front side (i.e., side of the fins **210***a* that faces the heat transfer side **121***a*). More specifically, the fins **210***a* may have a concave front side.

Concave configuration of the front side of the fins **210***a* may produce solid phase PCM that is offset at approximately the same distance from the heat transfer side **121***a* along the length of the thermal transfer assembly **120***a*. As such, the heat transfer side **121***a* of the thermal transfer assembly **120***a* may have no recess. Maintaining approximately the same distance from the heat transfer side **121***a* to the solid phase PCM may also facilitate approximately constant temperature along the heat transfer side **121***a* (e.g., near-freezing temperature). In addition, eliminating the recess from the heat transfer side **121***a* may allow the thermal transfer assembly **120***a* to include a greater amount of PCM (as compared with the thermal transfer assembly that has a recess). Consequently, the thermal transfer assembly **120***a* may maintain near-freezing temperature in the storage compartment for a longer duration during inactivity of the heat pump, as compared with the thermal transfer assembly that includes a recess.

As described above, in an embodiment, the storage apparatus may include a thermoelectric heat pump. FIG. **6**A illustrates an embodiment of a suitable configuration for a thermoelectric heat pump **190**. More specifically, as shown in FIG. **6**A, the thermoelectric heat pump **190** may produce heat flow from a cold side **191** to a hot side **192** thereof. Consequently, placing first ends of the heat pipes **200** in thermal communication within the cold side **191** of the thermoelectric heat pump **190** may cool the first ends of the heat pipes **200**. As described above, the second ends or portions of the heat pipes **200** may be positioned in and may be in thermal communication with the PCM. Accordingly, cooling the first ends of the heat pipes **200** may produce heat flow along the heat pipes **200** form the PCM and toward the first ends of the heat pipes **200**, where the heat may be further transferred to the cold side **191** and may be urged to flow from the cold side **191** to the hot side **192** (as indicated with the arrows) by applying a voltage across the thermoelectric heat pump **190**.

In an embodiment, a heat sink may be attached to the thermoelectric heat pump **190**, which may aid heat dissipation from the hot side **192** of the thermoelectric heat pump **190** (e.g., to the ambient environment). The particular configuration of the heat sink may vary from one embodiment to another. Generally, the heat sink may increase surface area exposed to a cooling medium, such as ambient air, as compared with a flat surface of the hot side **192**. Accordingly, the heat sink may improve conductive and convective heat transfer from the hot side **192**, thereby improving efficiency of the thermoelectric heat pump **190**.

For instance, a heat sink **230** may be in thermal communication with the hot side **192** and may include multiple linear ribs **231** that may span from a first edge of the hot side **192** to a second edge thereof. As noted above, however, the heat sink may have other configurations and may include nonlinear ribs, posts, other protrusions, or combinations thereof. In any event, the heat sink may increase heat transfer from the hot side **192**, thereby cooling the hot side **192** of the thermoelectric heat pump **190**.

In an embodiment, a cooling medium may be urged toward or into the heat sink to improve convective heat transfer therefrom. For example, as illustrated in FIG. **6**B, a fan **240** may provide air flow to or through a heat sink **230***a*. In some instances, the fan **240** may be attached to the heat sink **230***a*. Alternatively or additionally, the fan **240** may be attached to an outer shell of the storage apparatus or another portion thereof. In any case, the fan **240** may urge cooling medium toward the heat sink **230***a*, thereby increasing convective heat transfer therefrom.

The number, arrangement, and configuration of heat pipes may vary from one embodiment to the next. Generally, however, as illustrated in FIG. **7**, the heat pipe **200** may include an outer shell **201**, a wick **202** positioned within the outer shell **201**, and a vapor cavity **203** defined by the wick **202**. In some instances, the outer shell **201** may include stainless steel, copper, or other suitable thermally conductive material of sufficient strength.

The heat pipes **200** also may include a working fluid or coolant that may evaporate upon absorption of heat at a hot end **204** of the heat pipe **200**. Suitable working fluids may vary from one embodiment to the next and may depend, among other things, on the operating temperatures of the heat pipe **200** at the hot end **204** and at a cold end **205** thereof as well as on the pressure in the heat pipes **200**. Examples of working fluid include water, methanol, ethanol, ammonia, anhydrous ammonia, propylene, etc. In some embodiments, the heat pipe **200** may include ammonia or methanol.

In any case, as the working fluid at the hot end **204** absorbs heat from the PCM, which may be at about 0° C., the working fluid may evaporate, enter the vapor cavity **203**, and may move inside the vapor cavity **203** toward the cold end **205**, as indicated by the arrows. When the vapor reaches the cold end **205** (i.e., the end cooled by the heat pump), the vapor may be condensed to liquid and may be wicked into the wick **202**, as shown by the arrows. Subsequently, the liquefied working fluid may move back toward the hot end **204** (e.g., under force of gravity, under capillary force, etc.). In addition, such operation of the heat pipe **200** may be repeated in a cycle, thereby continuously removing heat from the PCM and transferring the removed heat to the heat pump.

While in the illustrated embodiment the storage apparatus includes at least one heat pipe, it should be appreciated that the storage apparatus may include any number of heat pipes or no heat pipes. For example, the heat pump may be in direct thermal communication with the PCM. Also, in some embodiments, any suitable thermally conductive material or structure may provide thermal communication between the heat pump and the PCM. In any case, operation of the heat pump may remove heat from the PCM, thereby changing phase of at least a portion of the PCM (e.g., from liquid to solid).

As described above, in some embodiments, the storage apparatus may include a freezer compartment, which may produce temperature below 0° C., sufficient to freeze water in the items stored in the freezer compartment. In an embodiment, a freezer compartment is configured to freeze blocks of ice. FIGS. **8**A-**8**B illustrate an embodiment of the freezer compartment **130**. In particular, FIG. **8**A shows that the freezer compartment **130** may include at least one heat pipe **200***b* in thermal communication with fins or plates **250**. The heat pipe **200***b* may be the similar to or the same as any of the heat pipes **200**, heat pipes **200***a* (FIGS. **2**A-**7**).

In some embodiments, the plates **250** may form or define walls or dividers within the freezer compartment **130**. For example, the freezer compartment **130** may include one or more walls that may form a container **260**, which may define the storage volume of the freezer compartment. The plates **250** may divide the volume defined by the container **260** into multiple sections or segments. In an embodiment, the plates **250** may divide the container **260** into four quadrants, each of which may store one or more temperature-sensitive items or materials **30**.

Moreover, in some instances, the plates **250** also may be in thermal communication with the container **260**. It should be appreciated that the plates **250** or the container **260** may include thermally conductive materials, which may increase the heat transfer area from the volume of the freezer compartment **130** to the heat pipe **200***b*. In other words, in an embodiment, the plates **250** or container **260** may operate similar to or the same as the fins **210** (e.g., FIG. **2**A).

Also, the freezer compartment **130** may include a heat pump in thermal communication with the heat pipe **200***b*. The heat pump of the freezer compartment **130** may be similar to or the same as the heat pump **190** (FIG. **2**A). In any event, the heat pump may cool a first end of the heat pipe **200***b*, thereby producing a temperature differential between the first and second ends of the heat pipe **200***b* and facilitating heat transfer from the freezer compartment **130** to the heat pump. As noted above, the heat pump may further transfer heat from a cold side thereof to a hot side thereof—subsequently, the heat on the hot side of the heat pump may be transferred to a cooling medium, such ambient air.

The freezer compartment **130** may be a dry compartment. In an embodiment, the freezer compartment **130** may include no PCM. Moreover, the freezer compartment **130** may control temperature of the temperature-sensitive items 30 at least in part by freezing one or more freezable packs, such as ice pack **270**. For example, ice pack **270** may include a freezable material encased in a shell (e.g., water encased in a plastic shell).

In some embodiments, the freezer compartment **130** may freeze the freezable material in the ice pack **270**. Hence, when the heat pump is not operating, the frozen ice packs **270** may maintain suitable temperature in the freezer compartment **130**, such as temperature below 0° C. That is, the frozen ice pack **270** may absorb energy from the volume of the freezer compartment **130** to melt the frozen material thereof, thereby maintaining the temperature in the freezer compartment **130** below freezing.

In additional or alternative embodiments, the freezer compartment **130** may be surrounded by PCM. In other words, the storage apparatus may include a chamber or a channel that surrounds the freezer compartment **130**, and which includes PCM. The PCM in such chamber may be frozen (e.g., via operation of heat pump as described above), and may further facilitate maintaining a below freezing temperature in the freezer compartment **130**.

In some embodiments, the ice pack **270** may be pressed against the plates **250** or container **260** to increase surface-to-surface contact therebetween and facilitate conductive heat transfer therebetween. For example, the freezer compartment **130** may include one or more clips **280** or other urging mechanism that may press the ice pack **270** against the plates **250**. More specifically, in an embodiment, two sides of the ice packs **270** may be pressed against the plates **250**.

Moreover, as illustrated in FIG. **8**B, the clips **280** may press the ice pack **270** against the plate **250** along some, most, or all of the height thereof. In other words, the freezer compartment **130** may include multiple clips **280** positioned at various heights within the container **260**. In some instances, the clips **280** may be positioned at different heights along one or more walls that define the container **260**. As such, in an embodiment, at least one face of the ice pack **270** may be pressed against the plate **250**.

The clip **280** may have any number of suitable configurations. For instance, the clip **280** may include compliant and sufficiently rigid or spring-like material, which may flex and press against a side of the ice pack **270**, thereby urging the ice pack **270** toward and against the plate **250**. As such, the ice pack **270** may be removed or replaced easily and without disassembly or unfastening of any elements or components of the freezer compartment **130**. Additionally or alternatively, the ice pack **270** may be pressed against the plate **250** or container **260** with one or more fasteners, buckles, latches, or the like. In any event, some embodiments may include ice pack **270** pressed against the plate **250** or container **260**.

As described above, the storage apparatus may control the temperature in the storage or in the freezer compartments by controlling operation of the one or more heat pump associated therewith. FIG. **9** illustrates a block diagram of a controller **300** of the storage apparatus according to an embodiment. For instance, the controller **300** may include at least one processor **310** coupled to a power source **150***a* (e.g., a solar panel) and to a power management unit **320**. The processor **310** may direct the power management unit **320** to provide power to a power output connection **330**.

For instance, a heat pump may be connected at power output connection **330**. The processor **310** may direct the power management unit **320** to supply power to the power output connection **330** and to the heat pump. As such, by controlling whether the heat pump operates or voltage provided to the heat pump, the processor **310** may control the temperature in the thermal transfer assembly or in the freezer compartment. In other words, for example, the controller may direct the heat pump to remove heat from the PCM until a predetermined portion of the PCM is at a suitable temperature or is in a solid phase. Consequently, the processor **310** also may control the temperature in the storage compartment (e.g., the processor **310** may control the temperature in the storage compartment to within about ±1° C.).

The processor **310** and the power management unit **320** also may adjust or transform the power received from the power source **150***a* to a suitable voltage or, for example, may convert the power to direct current. For instance, as described above, the power source **150***a* may include a solar panel. In some operating conditions, the output voltage from the solar panel may vary (e.g., due to variance in exposure to light). The processor **310** and the power management unit **320** may convert the power received from the solar panel to a suitable voltage, which may be further supplied to other elements or components of the storage apparatus, such as to the controller **300** and to the heat pump, among others. In other words, the controller **300** may be programmed to receive varying or variable voltage from the power source and to regulate such voltage to further provide suitable voltage to the heat pump.

In an embodiment, the power output connection **330** may be coupled to a memory **340**, which may contain operating instructions for the power output connection **330**. Specifically, in an embodiment, the memory **340** may include instructions about desirable temperature or temperature distribution in the PCM in the thermal transfer assembly. For example, the memory **340** may include instructions that relate change in volume of the PCM in the thermal transfer assembly to a suitable temperature distribution therein.

For instance, the PCM may include water. As PCM changes phase from liquid to solid, the total volume of the PCM in the thermal transfer assembly may change. Furthermore, the initial volume of the PCM (e.g., when all of the PCM is in a liquid phase) may be known or stored in the memory **340**. Accordingly, the processor may receive information about the volume (e.g., from one or more sensors) of the PCM and may calculate change in volume. Moreover, the processor **310** may calculate the amount of solid phase PCM. Hence, the instructions stored in the memory **340** may allow the processor **310** to determine the amount of solid phase PCM or temperature distribution in the thermal transfer assembly.

In additional or alternative embodiments, the instructions stored in the memory **340** also may allow the processor **310** to use one or more temperature readings from the PCM to control operation of the heat pump. For instance, the processor **310** may receive a single or multiple temperature readings (e.g., from sensors) indicative of the temperature in one or more zones in the PCM. When the temperature in the predetermined one or more zone in the PCM is at a predetermined level, as set in the instructions in the memory **340**, the processor **310** may stop operation of the heat pump.

In any case, the memory **340** may include instructions that may allow the processor **310** to determine whether to direct power management unit **320** to supply power to the heat pump connected at power output connection **330**, thereby controlling the temperature in the thermal transfer assembly and, thus, in the storage compartment. In an embodiment, the processor **310** may include similar instructions for operating the heat pump of the freezer compartment. For instance, the processor **310** may maintain operation of the freezer compartment heat pump until reaching a predetermined temperature level (e.g., −3° C.).

The memory **340** also may include instructions regarding priority or hierarchy of power needs. In other words, when the power received from the power source **150***a* is insufficient to power all elements or components connected at the power output connection **330**, the processor **310** may use the priority instructions to direct the power management unit **320** to provide power to elements or components indicated as having priority over other elements or components. For instance, processor **310** may give priority to providing power to the controller **300** over heat pump, and to the heat pump of the thermal transfer assembly over the heat pump of the freezer compartment. In an embodiment, the priority hierarchy may be as follows, listed from highest to lowest: controller **300** (or batter attached to the controller **300**, if any); heat pump of the thermal transfer assembly, fan for the heat sink of the heat pump (if any); heat pump of the freezer compartment; auxiliary power supply port.

Also, as described above, the storage apparatus may include an auxiliary power supply port, such as a USB port. The memory **340** may include priority instructions that may disable the auxiliary power supply port (at least temporarily) to facilitate operation of one or more heat pumps. Additionally, the memory **340** may include instructions for the processor **310** that may allow the processor **310** to direct the power management unit **320** to supply excess power, produced or otherwise available from the power source, to the auxiliary power supply port.

It should be appreciated that the supply of power to the controller **300** may include one or more batteries. In an embodiment, the battery may be a rechargeable battery and may power only the controller **300** (e.g., processor **310**, power management unit **320**, memory **340**, etc.). Hence, as mentioned above, when the controller **300** is operating only on such battery, the processor **310** may direct the power management unit **320** to prioritize power supply to the controller **300** before providing any power to other elements or components. In an embodiment, the storage apparatus may include one or more rechargeable batteries that may also provide sufficient power to operate one or more heat pumps. The processor **310** may direct the power management unit **320** to distribute power to such rechargeable batteries for charging as well as to distribute power therefrom for operation of various elements or components of the storage apparatus.

To receive information about the temperature or volume levels described above, the processor **310** may be coupled to one or more sensors **350**. For instance, the sensors **350** may include thermocouples (e.g., a temperature sensor), volumetric sensors, or the like. Moreover, in some instances, the processor **310** may store or log temperature or volume readings in the memory **340**. In additional or alternative embodiments, the controller **300** may include one or more I/O interface **360** coupled to the processor **310**. More specifically, the I/O interface **360** may provide information about operation of the storage apparatus or may allow programming of instructions to the memory **340**. For example, the controller **300** may be programmed to vary the predetermined voltage responsive a temperature of one or more of the storage compartment **110**, thermal transfer assembly **120**, or the freezer compartment **130**.

As described above, for example, the storage apparatus may include one or more displays. In an embodiment, I/O interface **360** may include such temperature displays. For instance, the processor **310** may direct the I/O interface **360** (temperature displays) to display temperature readings from the storage compartment, freezer compartment, PCM, or combinations thereof. In an example, such readings may be obtained by the sensors **350**. It should be appreciated that in additional or alternative embodiments, temperature displays may be unconnected to the processor **310** and may display readings directly from one or more sensor (or may be analog displays).

In an embodiment, a user or a manufacturer may provide and store instructions in the memory **340** of the controller **300**. For instance, such instructions may be provided through an input device (e.g., a keyboard) via the I/O interface **360**. In some embodiments, however, the controller **300** may be configured not to accept instructions from the user. More specifically, the controller **300** (e.g., the memory **340**) may not accept programming or other instructions, such as to avoid user errors that may be introduced with such instructions.

In an embodiment, a Bus **370** may couple the I/O interface **360**, sensors **350**, memory **340**, or combinations thereof to the processor **310**. Hence, in an embodiment, the processor **310** may simultaneously communicate with one or more of the I/O interface **360**, sensors **350**, or memory **340**. Furthermore, it should be appreciated that any of the processor **310**, power management unit **320**, power output connection **330**, memory **340**, sensors **350**, I/O interface **360**, or combinations thereof may be embodied in a single component or element included in the controller **300**.

The reader will recognize that the state of the art has progressed to the point where there is little distinction left between hardware and software implementations of aspects of systems; the use of hardware or software is generally (but not always, in that in certain contexts the choice between hardware and software can become significant) a design choice representing cost vs. efficiency tradeoffs. The reader will appreciate that there are various vehicles by which processes and/or systems and/or other technologies described herein can be effected (e.g., hardware, software, and/or firmware), and that the preferred vehicle will vary with the context in which the processes and/or systems and/or other technologies are deployed. For example, if an implementer determines that speed and accuracy are paramount, the implementer may opt for a mainly hardware and/or firmware vehicle; alternatively, if flexibility is paramount, the implementer may opt for a mainly software implementation; or, yet again alternatively, the implementer may opt for some combination of hardware, software, and/or firmware. Hence, there are several possible vehicles by which the processes and/or devices and/or other technologies described herein may be effected, none of which is inherently superior to the other in that any vehicle to be utilized is a choice dependent upon the context in which the vehicle will be deployed and the specific concerns (e.g., speed, flexibility, or predictability) of the implementer, any of which may vary. The reader will recognize that optical aspects of implementations will typically employ optically-oriented hardware, software, and or firmware.

The foregoing detailed description has set forth various embodiments of the devices and/or processes via the use of block diagrams, flowcharts, and/or examples. Insofar as such block diagrams, flowcharts, and/or examples contain one or more functions and/or operations, it will be understood by those within the art that each function and/or operation within such block diagrams, flowcharts, or examples can be implemented, individually and/or collectively, by a wide range of hardware, software, firmware, or virtually any combination thereof. In one embodiment, several portions of the subject matter described herein may be implemented via Application Specific Integrated Circuits (ASICs), Field Programmable Gate Arrays (FPGAs), digital signal processors (DSPs), or other integrated formats. However, those skilled in the art will recognize that some aspects of the embodiments disclosed herein, in whole or in part, can be equivalently implemented in integrated circuits, as one or more computer programs running on one or more computers (e.g., as one or more programs running on one or more computer systems), as one or more programs running on one or more processors (e.g., as one or more programs running on one or more microprocessors), as firmware, or as virtually any combination thereof, and that designing the circuitry and/or writing the code for the software and or firmware would be well within the skill of one of skill in the art in light of this disclosure. In addition, the reader will appreciate that the mechanisms of the subject matter described herein are capable of being distributed as a program product in a variety of forms, and that an illustrative embodiment of the subject matter described herein applies regardless of the particular type of signal bearing medium used to actually carry out the distribution. Examples of a signal bearing medium include, but are not limited to, the following: a recordable type medium such as a floppy disk, a hard disk drive, a Compact Disc (CD), a Digital Video Disk (DVD), a digital tape, a computer memory, etc.; and a transmission type medium such as a digital and/or an analog communication medium (e.g., a fiber optic cable, a waveguide, a wired communications link, a wireless communication link, etc.).

In a general sense, the various embodiments described herein can be implemented, individually and/or collectively, by various types of electro-mechanical systems having a wide range of electrical components such as hardware, software, firmware, or virtually any combination thereof; and a wide range of components that may impart mechanical force or motion such as rigid bodies, spring or torsional bodies, hydraulics, and electro-magnetically actuated devices, or virtually any combination thereof. Consequently, as used herein "electro-mechanical system" includes, but is not limited to, electrical circuitry operably coupled with a transducer (e.g., an actuator, a motor, a piezoelectric crystal, etc.), electrical circuitry having at least one discrete electrical circuit, electrical circuitry having at least one integrated circuit, electrical circuitry having at least one application specific integrated circuit, electrical circuitry forming a general purpose computing device configured by a computer program (e.g., a general purpose computer configured by a computer program which at least partially carries out processes and/or devices described herein, or a microprocessor configured by a computer program which at least partially carries out processes and/or devices described herein), electrical circuitry forming a memory device (e.g., forms of random access memory), electrical circuitry forming a communications device (e.g., a modem, communications switch, or optical-electrical equipment), and any non-electrical analog thereto, such as optical or other analogs. Those skilled in the art will also appreciate that examples of electro-mechanical systems include but are not limited to a variety of consumer electronics systems, as well as other systems such as motorized transport systems, factory automation systems, security systems, and communication/computing systems. Those skilled in the art will recognize that electro-mechanical as used herein is not necessarily limited to a system that has both electrical and mechanical actuation except as context may dictate otherwise.

In a general sense, the various aspects described herein which can be implemented, individually and/or collectively, by a wide range of hardware, software, firmware, or any combination thereof can be viewed as being composed of various types of "electrical circuitry." Consequently, as used herein "electrical circuitry" includes, but is not limited to, electrical circuitry having at least one discrete electrical circuit, electrical circuitry having at least one integrated circuit, electrical circuitry having at least one application specific integrated circuit, electrical circuitry forming a general purpose computing device configured by a computer program (e.g., a general purpose computer configured by a computer program which at least partially carries out processes and/or devices described herein, or a microprocessor configured by a computer program which at least partially carries out processes and/or devices described herein), electrical circuitry forming a memory device (e.g., forms of random access memory), and/or electrical circuitry forming a communications device (e.g., a modem, communications switch, or optical-electrical equipment). The subject matter described herein may be implemented in an analog or digital fashion or some combination thereof.

The herein described components (e.g., steps), devices, and objects and the discussion accompanying them are used as examples for the sake of conceptual clarity. Consequently, as used herein, the specific exemplars set forth and the accompanying discussion are intended to be representative of their more general classes. In general, use of any specific exemplar herein is also intended to be representative of its class, and the non-inclusion of such specific components (e.g., steps), devices, and objects herein should not be taken as indicating that limitation is desired.

With respect to the use of substantially any plural and/or singular terms herein, the reader can translate from the plural to the singular and/or from the singular to the plural as is appropriate to the context and/or application. The various singular/plural permutations are not expressly set forth herein for sake of clarity.

The herein described subject matter sometimes illustrates different components contained within, or connected with, different other components. It is to be understood that such depicted architectures are merely exemplary, and that in fact many other architectures can be implemented which achieve the same functionality. In a conceptual sense, any arrangement of components to achieve the same functionality is effectively "associated" such that the desired functionality is achieved. Hence, any two components herein combined to achieve a particular functionality can be seen as "associated with" each other such that the desired functionality is achieved, irrespective of architectures or intermedial components. Likewise, any two components so associated can also be viewed as being "operably connected," or "operably coupled," to each other to achieve the desired functionality, and any two components capable of being so associated can also be viewed as being "operably couplable," to each other to achieve the desired functionality. Specific examples of operably couplable include but are not limited to physically mateable and/or physically interacting components and/or wirelessly interactable and/or wirelessly interacting components and/or logically interacting and/or logically interactable components.

In some instances, one or more components may be referred to herein as "configured to." The reader will recognize that "configured to" can generally encompass active-state components and/or inactive-state components and/or standby-state components, unless context requires otherwise.

While particular aspects of the present subject matter described herein have been shown and described, it will be apparent to those skilled in the art that, based upon the teachings herein, changes and modifications may be made without departing from the subject matter described herein and its broader aspects and, therefore, the appended claims are to encompass within their scope all such changes and modifications as are within the true spirit and scope of the subject matter described herein. Furthermore, it is to be understood that the invention is defined by the appended claims. In general, terms used herein, and especially in the appended claims (e.g., bodies of the appended claims) are generally intended as "open" terms (e.g., the term "including" should be interpreted as "including but not limited to," the term "having" should be interpreted as "having at least," the term "includes" should be interpreted as "includes but is not limited to," etc.). It will be further understood by those within the art that if a specific number of an introduced claim recitation is intended, such an intent will be explicitly recited in the claim, and in the absence of such recitation no such intent is present. For example, as an aid to understanding, the following appended claims may contain usage of the introductory phrases "at least one" and "one or more" to introduce claim recitations. However, the use of such phrases should not be construed to imply that the introduction of a claim recitation by the indefinite articles "a" or "an" limits any particular claim containing such introduced claim recitation to inventions containing only one such recitation, even when the same claim includes the introductory phrases "one or more" or "at least one" and indefinite articles such as "a" or "an" (e.g., "a" and/or "an" should typically be interpreted to mean "at least one" or "one or more"); the same holds true for the use of definite articles used to introduce claim recitations. In addition, even if a specific number of an introduced claim recitation is explicitly recited, such recitation should typically be interpreted to mean at least the recited number (e.g., the bare recitation of "two recitations," without other modifiers, typically means at least two recitations, or two or more recitations). Furthermore, in those instances where a convention analogous to "at least one of A, B, and C, etc." is used, in general such a construction is intended in the sense the convention (e.g., "a system having at least one of A, B, and C" would include but not be limited to systems that have A alone, B alone, C alone, A and B together, A and C together, B and C together, and/or A, B, and C together, etc.). In those instances where a convention analogous to "at least one of A, B, or C, etc." is used, in general such a construction is intended in the sense the convention (e.g., "a system having at least one of A, B, or C" would include but not be limited to systems that have A alone, B alone, C alone, A and B together, A and C together, B and C together, and/or A, B, and C together, etc.). Virtually any disjunctive word and/or phrase presenting two or more alternative terms, whether in the description, claims, or drawings, should be understood to contemplate the possibilities of including one of the terms, either of the terms, or both terms. For example, the phrase "A or B" will be understood to include the possibilities of "A" or "B" or "A and B."

With respect to the appended claims, the recited operations therein may generally be performed in any order. Examples of such alternate orderings may include overlapping, interleaved, interrupted, reordered, incremental, preparatory, supplemental, simultaneous, reverse, or other variant orderings, unless context dictates otherwise. With respect to context, even terms like "responsive to," "related to," or other past-tense adjectives are generally not intended to exclude such variants, unless context dictates otherwise.

While various aspects and embodiments have been disclosed herein, the various aspects and embodiments disclosed herein are for purposes of illustration and are not intended to be limiting, with the true scope and spirit being indicated by the following claims.

What is claimed is:

1. A storage apparatus for storing at least one temperature-sensitive material at a controlled temperature, the storage apparatus comprising:

an enclosure structure including,

a storage compartment configured to hold the at least one temperature-sensitive material;

a thermal transfer assembly adjacent to and in thermal communication with the storage compartment, the thermal transfer assembly including,

a phase change material;

one or more heat pipes positioned at least partially within the phase change material, the one or more heat pipes including one or more exterior surfaces at least partially surrounded by the phase change material; and

a plurality of thermally conductive fins in thermal communication with the one or more heat pipes and positioned at least partially within the phase change material;

a thermoelectric heat pump in thermal communication with the one or more heat pipes;

a heat sink in thermal communication with the thermoelectric heat pump;

at least one temperature sensor configured to measure temperature in at least one of the storage compartment or the thermal transfer assembly; and

a controller operably coupled to the thermoelectric heat pump and to the at least one temperature sensor, the controller being configured to direct the thermoelectric heat pump to controllably cool the phase change material so that a temperature of the storage compartment is controlled responsive to information from the at least one temperature sensor.

2. The storage apparatus of claim **1**, wherein the storage compartment is at least partially defined by at least one first wall and at least one second wall that separates the storage compartment from the thermal transfer assembly, the at least one first wall has a first thermal conductivity and the at least one second wall has a second thermal conductivity that is higher than the first thermal conductivity.

3. The storage apparatus of claim **2**, wherein the at least one first wall has thermal conductivity of less than about 0.3 W/(m×K).

4. The storage apparatus of claim **2**, wherein the at least one first wall includes a vacuum chamber.

5. The storage apparatus of claim **2**, wherein the at least one first wall includes aerogel.

6. The storage apparatus of claim **2**, wherein the thermal transfer assembly includes one or more third walls having the first thermal conductivity.

7. The storage apparatus of claim **1**, further comprising a lid sized and configured to cover one or more of the storage compartment or the thermal transfer assembly.

8. The storage apparatus of claim **1**, wherein the plurality of thermally conductive fins are oriented substantially horizontally.

9. The storage apparatus of claim **8**, wherein at least one of a size, shape, or material of the plurality of thermally conductive fins or the one or more heat pipes are selected to partially control a freezing profile of the phase change material so that a portion of the phase change material adjacent to the storage compartment is not frozen.

10. The storage apparatus of claim **1**, wherein the one or more heat pipes are spaced away from at least one wall that separates the thermal transfer assembly from the storage compartment.

11. The storage apparatus of claim **1**, wherein the phase change material includes water.

12. The storage apparatus of claim **1**, wherein the phase change material includes Puretemp 1.

13. The storage apparatus of claim **1**, wherein the phase change material exhibits a thermal resistance in a liquid phase that is higher than in a solid phase.

14. The storage apparatus of claim **1**, further comprising a power source coupled to one or more of the controller and the thermoelectric heat pump.

15. The storage apparatus of claim **14**, wherein the power source includes one or more photovoltaic panels.

16. The storage apparatus of claim **15**, wherein the controller is configured to divert excess power produced by the photovoltaic panels to one or more external loads.

17. The storage apparatus of claim **16**, further comprising a USB charging port operably coupled to the controller.

18. The storage apparatus of claim **17**, wherein at least one of the one or more external loads can be produced by a device connected to the USB charging port.

19. The storage apparatus of claim **15**, wherein the controller is programmed to receive varying voltage from the one or more photovoltaic panels and supply power to the thermoelectric heat pump at one or more predetermined voltages.

20. The storage apparatus of claim **19**, wherein the controller is programmed to vary the predetermined voltage at least based on a temperature of one or more of the storage compartment or the thermal transfer assembly.

21. The storage apparatus of claim **20**, wherein the controller is programmed to control the thermoelectric pump in a manner that maintains a predetermined temperature range in the storage compartment.

22. The storage apparatus of claim **21**, wherein the predetermined temperature range is about 2° C. to about 8° C.

23. The storage apparatus of claim **1**, wherein the controller is configured to control power delivered to the thermoelectric heat pump.

24. The storage apparatus of claim **1**, wherein the heat sink include a cooling fan.

25. The storage apparatus of claim **24**, wherein the controller is configured to selectively provide power to one or more of the controller, thermoelectric heat pump, or the cooling fan of the heat sink.

26. The storage apparatus of claim **1**, further comprising a freezer compartment adjacent to at least one of the storage compartment or the thermal transfer assembly and separated therefrom by at least one wall.

27. The storage apparatus of claim **26**, wherein the freezer compartment includes:

a freezer space sized and shaped to house one or more freezable packs;

a plurality of additional heat pipes in thermal communication with the freezer space; and

an additional thermoelectric heat pump in thermal communication with the plurality of additional heat pipes.

28. The storage apparatus of claim **27**, wherein the controller is programmed to distribute power from a power source to the additional thermoelectric heat pump.

29. The storage apparatus of claim **1**, wherein at least one of the one or more heat pipes is a wicked heat pipe.

30. The storage apparatus of claim **29**, wherein the at least one of the one or more heat pipes includes a coolant therein.

31. The storage apparatus of claim **30**, wherein the coolant includes at least one or more of methanol, ammonia, anhydrous ammonia, or propylene.

32. The storage apparatus of claim **27**, wherein the one or more additional heat pipes is in thermal communication with a plurality of thermally conductive plates, and the plurality of thermally conductive plates are in thermal communication with the freezer space.

33. The storage apparatus of claim **32**, further comprising an urging mechanism configured to press one or more freezable packs against a wall of the freezer space.

34. The storage apparatus of claim **26**, further comprising a chamber at least partially surrounding the freezer compartment, the chamber including an additional phase change material therein.

35. The storage apparatus of claim **26**, further comprising a second temperature sensor configured to measure temperature in the freezer compartment.

36. The storage apparatus of claim **35**, further comprising a display operably coupled to the second temperature sensor and configured to display temperature sensed by the second temperature sensor.

37. The storage apparatus of claim **1**, further comprising a display operably coupled to the controller and configured to display temperature sensed by the at least one temperature sensor.

38. The storage apparatus of claim **1**, wherein the thermal transfer assembly includes a heat transfer side in thermal communication with the storage compartment, and the heat transfer side include a recess therein.

39. The storage apparatus of claim **38**, further comprising thermal insulation located in the recess.

40. A method of maintaining at least one temperature-sensitive material in a storage apparatus at a temperature lower than an ambient temperature, the method comprising:

placing the at least one temperature-sensitive material in a storage compartment of the storage apparatus that is adjacent to and in thermal communication with a thermal transfer assembly of the storage apparatus having a phase change material disposed therein; and

controllably changing a phase of a portion of the phase change material by removing heat therefrom via one or more heat pipes attached to a thermoelectric heat pump so that a first portion of the phase change material is in a solid phase and a second portion of the phase change material is in a liquid phase that is disposed between the storage compartment and the first portion.

41. The method of claim **40**, further comprising controlling the thermoelectric heat pump to remove heat from the phase change material responsive to a change in temperature in one or more of the storage compartment, the thermal transfer assembly, or the phase change material.

42. The method of claim **41**, wherein controlling the thermoelectric heat pump to remove heat from the phase change material responsive to a change in temperature in one or more of the storage compartment, the thermal transfer assembly, or the phase change material includes maintaining a temperature in the storage compartment in a range of about 2° C. to about 8° C.

43. The method of claim **40**, wherein controllably changing a phase of a portion of the phase change material by removing heat therefrom via a thermoelectric heat pump includes transferring heat from the change phase material to one or more heat pipes.

44. The method of claim **43**, further comprising transferring heat from the one or more heat pipes to the thermoelectric heat pump, thereby cooling the one or more heat pipes.

45. The method of claim **40**, further comprising distributing power from one or more photovoltaic panels to the thermoelectric heat pump.

46. The method of claim **45**, further comprising diverting excess power from the photovoltaic panels to one or more external loads.

47. The method of claim **45**, further comprising regulating a voltage supplied to the thermoelectric pump.

48. A storage apparatus for storing at least one temperature-sensitive material at a controlled temperature, the storage apparatus comprising:

an enclosure structure including,

a storage compartment configured to hold the at least one temperature-sensitive material;

a thermal transfer assembly adjacent to and in thermal communication with the storage compartment, the thermal transfer assembly including,

a phase change material disposed therein; and

a plurality of heat pipes positioned at least partially within the phase change material; and

a plurality of thermally conductive fins in thermal communication with the plurality of heat pipes, the plurality of thermally conductive fins oriented substantially horizontally;

a thermoelectric heat pump in thermal communication with the plurality of heat pipes; and

a controller operably coupled to the thermoelectric heat pump and programmed to controllably cool the phase change material;

wherein at least one of a size, shape, or material of the plurality of thermally conductive fins and the plurality of heat pipes are selected in combination with power to be provided to the thermoelectric heat pump to partially control a freezing profile of the phase change material so that a portion of the phase change material adjacent to the storage compartment is not frozen.

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